UNIVERSITY OF ALBERTA

A FRAMEWORK FOR ERGONOMIC ASSESSMENT OF RESIDENTIAL CONSTRUCTION TASKS

By

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Abstract

Residential construction activities are predominantly physical in nature and are usually executed in uncomfortable environments at a fast pace. Workers in this industry require physical stamina as daily tasks often require prolonged standing, bending, stooping, material handling, working in crowded spaces and sometimes exposure to adverse weather conditions. This places varying amounts of stress on the musculoskeletal system (muscles, tendons, ligaments and bones) of the worker and increases the potential risk of work-related musculoskeletal disorders (WRMSDs) which may in time deteriorate into permanent disability and, consequently, loss of ability to work. Applicable strategies are required to identify and control or eliminate the potential for development of WRMSDs by controlling or eliminating causal risk factors. The goal of this research is to develop a framework for ergonomic assessment of residential construction tasks. This goal is realized through the development of three ergonomic assessment models: (i) an observation-based assessment model (*ErgoCheck*), (ii) a biomechanical assessment model (*ErgoBioMCheck*), and (iii) a discrete event-simulation-based assessment model application (*ErgoSymulate*). *A fatigue-productivity relationship* model has also been developed as part of this study. Five (5) case studies are presented based on an assessment of factory-based residential construction wall and floor panel framing processes conducted in collaboration with an Alberta-based home builder. These case studies are used to assess the applicability and validity of the developed models. The results have shown acceptable correlation with existing models and compliance with evidence and theories found within ergonomics and construction literature. Further experimental and quantitative validation is recommended.

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Chapter 1 Introduction

1.1 Research Motivation

Work conditions which expose the muscles, joints, tendons, ligaments, and nerves to physical risk factors such as awkward postures, high force, repetitive motions, contact stress, static loading (lifting), segmental or whole body vibration, and heat and cold cause or increase the potential injury due to exertion or overexertion. The risk of injury is related to the activity duration, frequency, intensity or a combined exposure to risk factors. According to the Alberta Workers Compensation Board's industry synopsis for residential general contractors, five types of accidents are prevalent in the industry: falls, overexertion, struck by an object, bodily reaction and exertion, and slip. These accidents affect various segments of the body (back, foot/ankle, neck, hands, trunk, hand(s)/wrist(s), and knees), and have resulted in numerous claims and lost time days (WCB Alberta 2011). The construction industry has addressed accidents (falls, struck by objects, and slips) through regulations and standard practices involving the use of appropriate personal protective equipment (PPE), colour coding, signs, and signals. However, accidents related to exertion and overexertion leading to sprains/strains (musculoskeletal disorders/injuries) is difficult to identify and control. Symptoms of musculoskeletal disorders may manifest themselves immediately or after hours, days, months or even years of continuous exposure. As the physical demand of the task exceeds the physiological capability of the worker, there is an increased tendency to develop either an immediate symptom (sprain or strain) or a cumulative trauma injury (CTD) over time. The adoption of safe ergonomic principles for work execution could potentially reduce worker compensation costs by up to 80 percent.

1.2 Research Objective

The objective of this research is to

"***Develop a framework for assessing the ergonomic risk of residential construction tasks and measure the impact of such risk on the productivity of the work and worker***".

This objective shall be accomplished by:

- developing an observation based model for ergonomic assessment and rating of construction tasks (***ErgoCheck***);
- developing a kinematics based biomechanical (mathematical) model for assessment of instantaneous and cumulative lower-back compression and shear forces, torques and stress during construction work (***ErgoBioMCheck)***;
- applying a discrete-event simulation technique (***ErgoSymulate***) for the purpose of assessing ergonomic risks while performing residential construction work activities; and
- developing a novel fatigue-productivity relationship model.

This aforementioned objective is based on the hypothesis that

"Careful ergonomic-based design of construction activities will improve construction productivity."

The ergonomic-based design of work tasks and activities entails proactive assessment of ergonomic risks resulting from the physiological, psychological, and psychosocial demands placed on the worker(s) based on the (i) task(s) to be performed; (ii) techniques used (including postures adopted); (iii) available or recommended tools (and clothing); and (iv) work area (layout, height of work station, supports) and the capability of the worker to safely and efficiently execute the designed activities.

This research examines state-of-the-art literature, and techniques in assessment of ergonomic risks with a focus on applications adaptable to manufactured residential construction tasks performed at offsite factories (modular or panelized construction delivery methods) are reviewed. Best practices and methodologies of various occupational safety and health organizations and industry are referenced. The economic and social impact of these disorders and the impact of injury on productivity are presented in an attempt to show the negative impact of musculoskeletal disorders aggravated by current ergonomic practices both on the economy (nationally and internationally) and on workers' health. This study is focussed primarily on North American (particularly Canadian) ergonomic legislation and occupational health and safety practices as they pertain to musculoskeletal disorder prevention in construction occupations. Although the approaches target North American residential construction projects, they could be applied globally to a variety of building projects. Ergonomic hazards from work tasks are assessed and models and methods developed for the purpose of quantifying, classifying, and rating work-related risks. The potential effect of poor ergonomic practices on work and worker productivity has been reviewed and a new fatigue-productivity model developed. Existing rest allowance models have also been reviewed as part of this study.

The terms “injury” and “disorder” are used interchangeably within the existing literature and hence the two will be used similarly in this thesis. Likewise, the terms “risk” and “hazard” are used interchangeably.

1.3 Thesis organization

This thesis consists of five chapters. Chapter 1 introduces the research problem, presents the research hypothesis, objectives, scope, and organization. Chapter 2 presents a literature review on ergonomics and work-related musculoskeletal disorders (WRMSDs); cost of WRMSDs; current workplace ergonomics legislation; state-of-the-art research in ergonomics and its applications in residential construction; applications and models for ergonomics applications; relationship between ergonomics and productivity; exposure-response relationships; and a review of validation techniques. Chapter 3 presents the ergonomic assessment framework and developed ergonomic assessment techniques and models. Chapter 4 presents case studies illustrating the failure of current ergonomics research and the implementation of the proposed research models for assessment of ergonomic risk. Chapter 5 presents general discussions and conclusions based on the case study results; the success, limitations, contributions, and future research work are also summarized within this chapter.

Chapter 2 Literature Review

2.1 Ergonomics and Work-Related Musculoskeletal Disorders

2.1.1 Background on Ergonomics and Work-Related Musculoskeletal Disorders (WRMSDs)

The word, ergonomics, has its origin in two Greek words, *ergon* and *nomos*, which together mean to "work (by) natural laws" (Bernold and AbouRizk 2010). "Ergonomics" is defined more pointedly as the science and practice of designing jobs and workplaces to match the capabilities and limitations of the human body. It is further defined as a study of relationships between work and physical and cognitive capabilities of people which may involve altering, manipulating, or redesigning the job (tools, tasks, and environment) to fit the worker rather than forcing the worker to fit the job (Keyserling et al. 1993). It aims to match or fit the given work conditions and demands on the human physical and cognitive capacity, and to prevent injuries by identifying tasks in the workplace that pose a hazard for work-related musculoskeletal disorders (WRMSDs). Ergonomic analysis is based on human anthropometry, a branch of the human sciences that deals with body measurements. WRMSDs involve a group of non-traumatic soft tissue musculoskeletal disorders (MSDs) and conditions resulting from work execution requirements and layout (work station design) (U.S. Department of Labor and Industries 2003).

Kumar (2001) defines injury as a mechanical disruption of tissues resulting in inflammation and pain and perhaps other biochemical responses. The onset of an injury is either sudden, from an instantaneous exertion event, or a gradual mechanical degradation of the tissue. A disorder, on the other hand, is defined as any malfunction of an organ or tissue without a mechanical perturbation (cause or trigger) of the tissues. This is usually gradual in nature and mediated by a pathogen or a pre-pathological progression. The tissues which frequently sustain injury from exposure to occupational biomechanical hazards are ligaments, tendons, and muscles. WRMSDs are caused by either gradual or instantaneous injury to the nerves and tissues due to a subjection of the musculoskeleton to stress from work activities such as holding a saw, swinging a hammer, bending the neck or back, flexing or extending the wrists, pinching, gripping, and lifting (U.S. Department of Labor and Industries 2003). Common WRMSDs include tendon disorders (bursitis, tendonitis, ganglion, and trigger-finger); nerve disorders (carpal tunnel syndrome); and neurovascular disorders (Reynaud's phenomenon or white finger syndrome) (Hedge 2010).

Other factors, such as age, gender, body size and strength (anthropometry), years of experience, state of mind, type of construction method, type of tools, location where work is executed, and the adopted construction method (conventional, modular and panelized), can influence the pace of work and exposure to risks leading to WRMSDs. WRMSDs can be categorized as either (i) sprains and strains or (ii) cumulative trauma disorders. Sprains and strains are injuries to connective tissue caused by a single forceful event, such as lifting a heavy object in an awkward position. Such injuries are common to large body segments (such as back, legs, and shoulders). Sprains and strains are also referred to as overexertion injuries, as they typically result from excessive physical effort (beyond the worker's physiological capacity) directed at an outside source—usually a non-impact-related activity such as lifting, pulling, pushing, turning, wielding, carrying, or throwing. CTDs are injuries to the soft tissues (e.g., fingers, wrists, elbows, and neck) caused by prolonged exposure to multiple ergonomic risk factors. CTDs are also referred to as "bodily reaction and exertion injuries," and they generally result from such work activities as walking, climbing, or bending. Epidemiological evidence exists linking the development of MSDs to work conditions. Such evidence shows that a variety of disorders can be linked to exposure to repetitive activities, force/static loading, contact stress, environmental conditions, organizational factors, vibration, and physical and emotional stress (Bernard 1997; US. Department of Health and Human Services 1997).

WRMSDs within the construction industry are of major concern, with high rates recorded annually (BLS 2010; Karwowski and Marras 2003). Residential construction industry reports show high incidence of WRMSDs (BLS 2006; Workers day memorial report 2009; WCB Alberta 2010; ACSA 2009; Spielholz et al. 2006) leading to costly claims and lost work time. According to the National Center for Health Statistics, "musculoskeletal disorders, including carpal tunnel syndrome, are among the most prevalent medical conditions in the U.S., affecting 7% of the population and account for 14% of physician visits and 19% of hospital stays" (Kugel 2005). Based on a report by the National Institute for Occupational Safety and Health, 62% of persons with musculoskeletal disorders report some degree of limitation in activity, compared to 14% of the population at large, (Rosenstock 1997). The U.S Bureau of Labor Statistics calculated the percent distribution of nonfatal occupational injuries and illnesses involving days away from work by industry and selected the natures of injury or illness. Their injury statistics for the residential construction reveal that sprains and strains made up 34.5% of claimed injuries for 2006 (BLS 2006). In Canada, the Alberta Construction Safety Association (ACSA) industries injury report for 2008 shows that 93.7% of lost-time claims and 95.4% of disabling injury claims are caused by traumatic injuries and disorders. Out of these traumatic injuries and disorders, sprains, strains, and tears (WRMSDs) account for 46.8% of the disabling injury claims submitted (Table 2.2), with the trunk and back recorded as the most commonly injured body parts, accounting for over 34.4% of total lost-time claims and 33.2% of disabling injury claims. Based on the type of exposure leading to injury, bodily reaction or exertion leads at 39.5% (Table 2.3) (ACSA 2009). Statistics show bodily reaction, exertion and overexertion injuries as leading causes of work-related injuries and lost-time claims in construction and other industries compared to other causes of injury (Figure 2.1; Figure 2.2).

Older injury reports also validate traumatic injuries as the top injuries for lost-time claim costs (NSC 1995; Webster and Snook 1994; Frymoyer and Cats-Baril 1991). WCB Alberta residential construction contractor statistics for 2006-2010 recorded 285 claims of bodily reaction and exertion injuries, which were the second highest cause of lost time claims (35.8%), only surpassed by falls (36.64%) for the given period (WCB Alberta 2011). Statistics from Europe also confirm the prevalence of WRMSDs in construction and other industries (Schneider et al. 2010). As can be seen, WRMSD costs are extreme and will accumulate over time if concise mitigation strategies are not adopted.

Table 2.1: Rate of Musculoskeletal Disorders with Days Away from Work, 2007 by Industry.

Industry Sector	**Massachusetts***	**United States***
All Private Industries	52.2	35.2
Transportation & Warehousing	170	83
Health Care and Social Assistance	97.8	55.4
Agriculture, Forestry, Fishing & Hunting	88.9	29.5
Construction	**84.3**	**41.4**
Retail Trade	65.6	42.5
Wholesale Trade	65.6	42.7
Other Services	38.5	21.9
Manufacturing	48.9	41.1
Utilities	55	35.4
Real Estate and Rental, Leasing	12.1	29.9
Leisure and Hospitality	23.6	19.8
Education Services	26.2	15.2
Information	18.8	18.2
Professional and Business Services	25.8	16.8
Finance & Insurance	1.4	5.8

* Rates are expressed per 10,000 full-time workers.

Table 2.2: Type of injury or disease (WRMSD) - Alberta: 2008

Injury or disease	**% of Total Lost-Time Claimed injuries**	**% of Total Disabling injuries**
Traumatic Injuries/disorders	93.7%	95.4%
Sprains, Strains and Tears	41.9%	46.8%
Fractures and Dislocations	15.1%	9.8%
Open Wounds	11.1%	12.5%
Surface Wounds and Bruises	11.6%	13.9%
Burns	1.8%	1.4%
Other traumatic injuries and disorders	12.1%	11.0%
Other diseases and infections (known/unknown causes)	6.3%	4.60%
Total	**100.0%**	**100.0%**

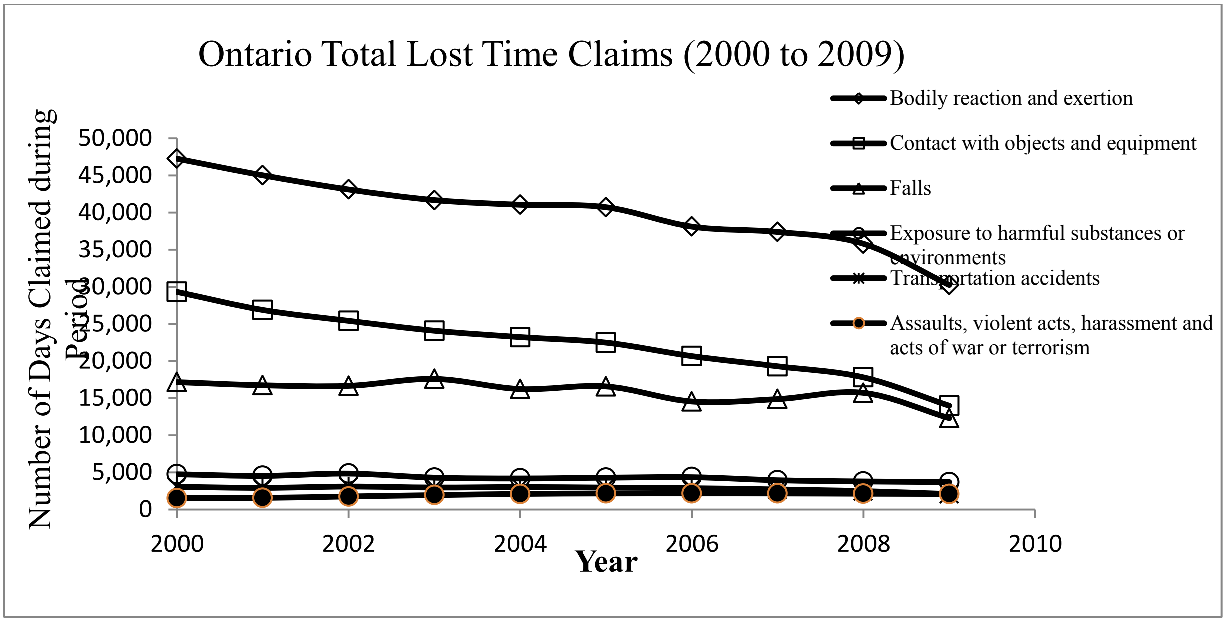


Figure 2.1: Ontario - Total LTC from WRMSDs (All Industries).

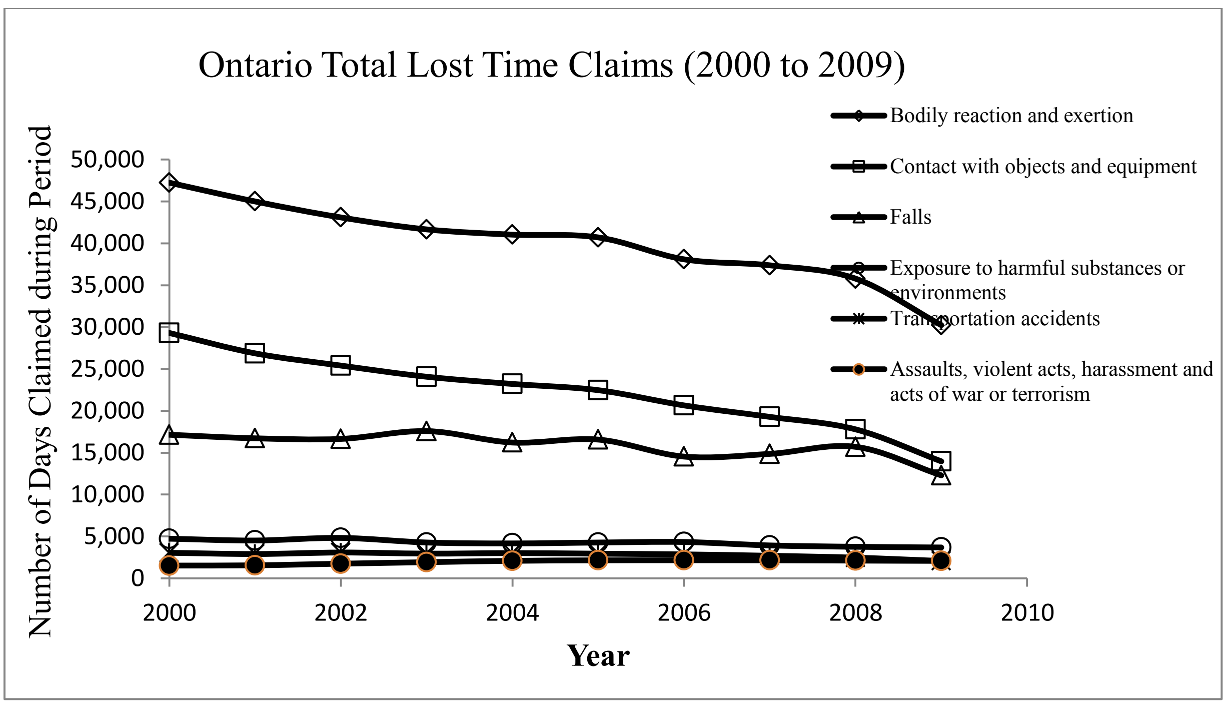


Figure 2.2: Ontario - Total LTC from WRMSDs (All Industries).

Physical work activities lead to fatigue of the muscles (local muscle fatigue) over time, in turn leading to a reduction in muscle capacity and consequently increasing potential for injury (ergonomic hazard). Fatigue also influences work rate and output (productivity), which may in turn result in schedule overruns. Work-related injuries result in physical pain, suffering, and possibly lost income for the worker if they are unable to work. The employer experiences a reduction in productivity and increased scheduling inconsistencies resulting from increased absenteeism (lost time due to injury), work inefficiency, and potentially increased workers' compensation premiums, while the government witnesses an increase in health care costs. The resultant productivity decline, absenteeism, high lost-time claims costs, increased insurance premiums, project delays, unexpected scheduling changes, recruitment and training costs are cumulative, unexpected costs which add to the project’s indirect costs and may impact the company’s competitiveness. Painful, disabling, and expensive, these work-related injuries and disorders are preventable through an adoption of practical, proactive, and effective ergonomic assessment techniques and controls.

2.1.2 Ergonomic Risk Factors

The Canadian Centre for Occupational Health and Safety (CCOHS) defines a hazard as any source of potential damage, harm or adverse health effects on something or someone under certain conditions at work. A hazard is thus anything that can cause harm or adverse effects. These may be biological, physical, ergonomic, chemical, psychosocial or safety. Work related hazards include materials, substances, processes or practices which could cause harm or adverse health effect to a person under certain conditions. Risks on the other hand have been defined by CCOHS as the chance or probability that a person will be harmed or experience an adverse health effect if exposed to a hazard. It may also apply to situations with property or equipment loss (CCOHS 2009).

Ergonomic risk factors are workplace elements (conditions) and actions, or a combination of both, which cause physical stress to the body, thus increasing the risk of WRMSD. These include forceful exertions, awkward postures, repetitive exertions, segmental and whole body vibration, contact stress, organizational factors, and environmental factors.

(i) Forceful or static exertions: These pertain to the amount of muscular effort required to perform a task. Greater force exertion results in an increased risk potential for WRMSD. High force has been associated with WRMSDs at the shoulder/neck, the low back, and the forearm/wrist/hand.

(ii) Awkward Posture: This is the relative orientation or position of the body segments while performing work activities. Body postures deviated from the neutral posture are associated with an increased risk for injury. It is generally considered that the more a joint deviates from the neutral (natural) position, the greater the risk of injury. Awkward postures include bending, reaching, twisting, squatting, and kneeling (Straker et al. 1997; Huysmans et al. 2008). Posture angles are measured in terms of the number of degrees a specific joint deviates from the neutral position. Body landmarks for measuring angles are described in the American Academy of Orthopedic Surgeons' "Joint Motion Methods of Measuring and Recording" (1963). In work situations, posture can be measured by live (visual) observations, as well as through the use of still photographs, videotapes, goniometers or postural tracking equipment, and computerized data acquisitions systems. Aaras et al. (1988) present work supporting the notion that postural angles are an indicator of postural load and thus lead to WRMSDs (predominantly back pains) in occupational work situations.

(iii) Repetition: This refers to the frequency or number of similar exertions performed during a task. Repeated exertion, including the use of hand tools, has been frequently identified as a WRMSD risk factor. Repetitive tasks are tasks with cycle times less than thirty (30) seconds or tasks where 50% of the cycle is performing the same fundamental activities (Silverstein et al. 1986; Moore and Wells 2005). Generally, the greater the number of repetitions, the greater the degree of risk of cumulative trauma injuries (Kumar 2001). However, there is no specific repetition limit or threshold value (cycles/unit of time, movements/unit of time) associated with injury.

(iv) Contact Stress: This implies the repeated contact of the body with a hard surface or edge, such as the corner of a table or tool (such as during carpet laying tasks).

(v) Hand-Arm Vibration: This pertains to vibration applied to the hand/arms through a tool or piece of equipment. This can cause a reduction in blood flow to the hands/fingers (resulting in Raynaud's disease or vibration white finger). Also, it can interfere with sensory receptor feedback, leading to an increase in the handgrip force needed to hold the tool. Furthermore, a strong association has been reported between carpal tunnel syndrome and segmental vibration. Measurements of the maximum amount of vibration available to the hand (such as "hazard level") are performed using the "basicentric" system. Hand-arm vibration measurements and analyses should be performed according to ANSI S3.34, ACGIH-TLV, and NIOSH 89-106 recommendations.

(vi) Organizational Risk factors: This refers to aspects of how a job is organized. Examples include monotonous tasks, machine paced work, inadequate breaks, and multiple deadlines.

(vii) Environmental Risk factors: This refers to the prevailing conditions of the work environment and their adverse effect on the worker's health. These include sources and levels of light that provide too much or too little illumination, cold and excessively warm temperatures (including snow, space heating), wind, and noise.

2.1.3 Scientific Explanation of development of WRMSDs

Due to the multi-factorial nature of WRMSDs, many studies have been conducted in recent years which have established a basis for ergonomic risk assessments. In the last two decades, progress has been made in achieving better understanding of the causes of musculoskeletal injuries through research involving personal, biomechanical, and psychosocial work factors, as well as in understanding the relationship between the organization and quality of work area/task design and injury potential (Malchaire 2001; Stal et al. 2003). Further research awareness has led to quantification of the contributing factors to CTDs associated with construction tasks as well as the limits for sprains and strains in the upper and lower extremities. Extensive research relating musculoskeletal injuries to work tasks also exists (Brinckmann et al. 1998; WorkSafeBC 2008; Keyserling 1992). Other studies have investigated how construction work-based factors lead to CTDs and also determine the prevalence of CTDs in construction (Killough 1996). WorkSafeBC (2008) has assessed the risk of sprains and strains in construction and the mechanisms of injury. Stubbs and Nicholson (1979) investigated material handling and back injuries in construction; Hess et al. (2010) discussed the ergonomic evaluation of masons laying concrete masonry units and autoclaved aerated concrete. Entzel et al. (2007) developed best practices for preventing musculoskeletal disorders in masonry.

Three models found in the ergonomics literature have described the development of work-related musculoskeletal disorders. Armstrong et al. (1993) illustrated that work activities produce internal forces which act upon body tissues (dose), stimulating a biomechanical or physiological response which may limit the worker's functional ability (Figure 2.3). Claudon and Cnockaert (1994) presented a model showing that stress levels exceeding an individual's functional capacity result in an increased risk of WRMSDs (Figure 2.4); Kumar (2001) showed how MSDs develop as a result of multiple factors (genetic, anthropometry, biomechanical and psychological) (Figure 2.5).

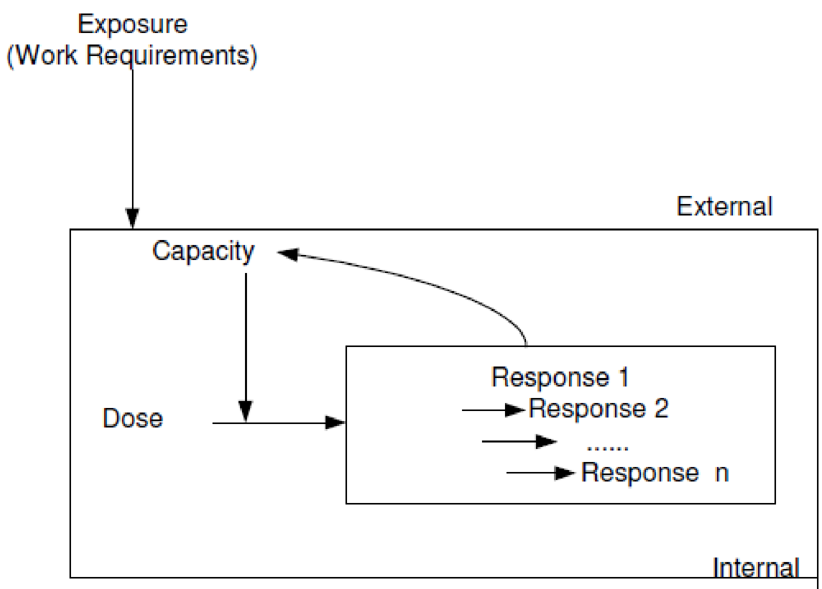


Figure 2.3: Risk factor dose-response model (Armstrong et al. 1993)

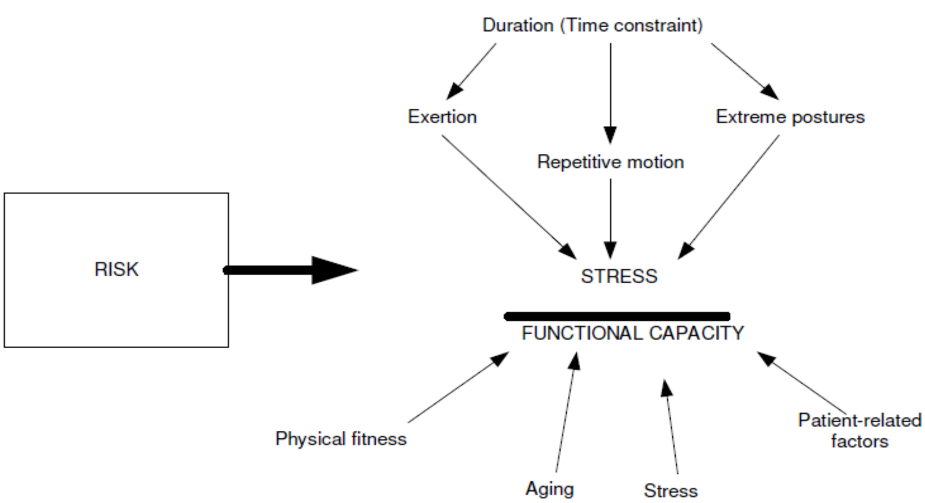


Figure 2.4: Risk factors for musculoskeletal disorders (Claudon and Cnockaert 1994)

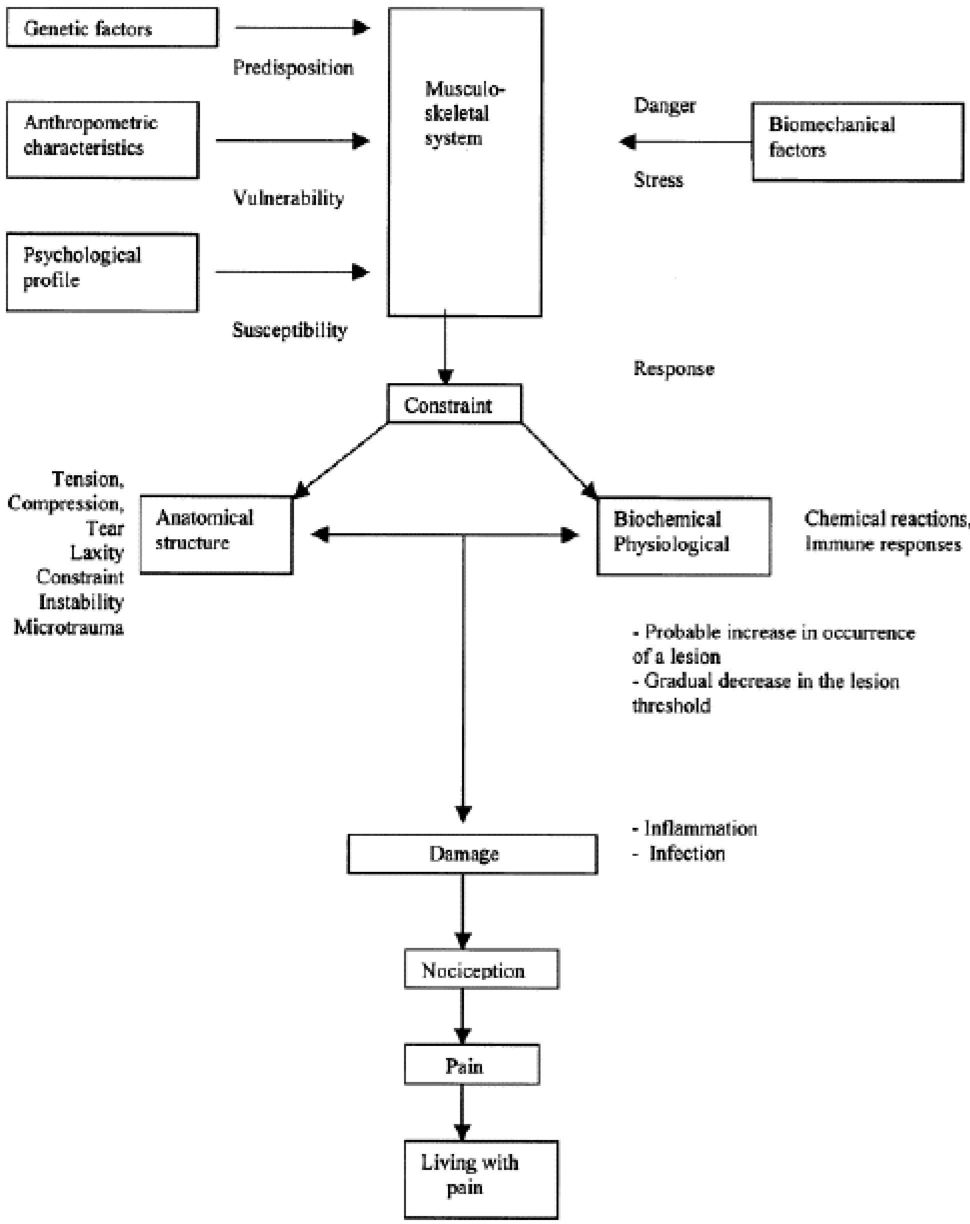


Figure 2.5: Multifactorial interactions resulting in musculoskeletal disorders (Kumar 2001)

2.2 Literature review on the Cost of Work-Related Musculoskeletal Disorders

2.2.1 Global Cost of Work-Related Musculoskeletal Disorders

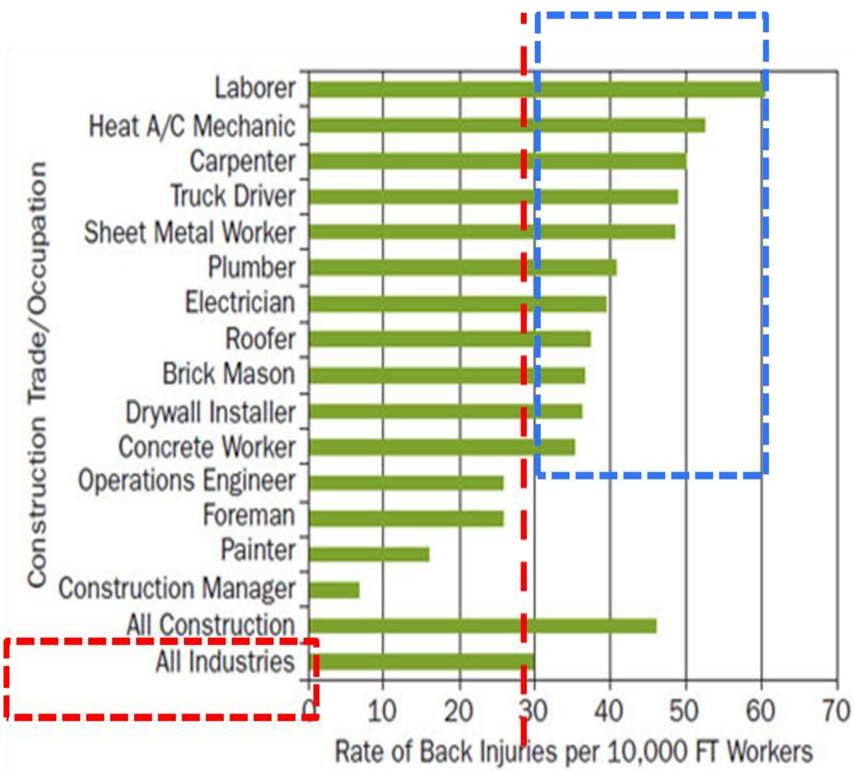
Various national and international statistics show that construction workers are at a high risk of developing WRMSDs. According to the Bureau of Labor Statistics, trades workers experience a work-related injury and illness rate that is higher than the national average (BLS 2010); The

WRMSDs incidence report for 2007 by the United States Bureau of Labor Statistics showed residential construction to be leading all other industries (Figure 2.6 and Table 2.1). From Table 2.1, 41.4 per 10,000 residential construction workers reported WRMSD incidents compared to about 35.2 per 10,000 workers from other industries. More than 357,000 cases of WRMSDs resulting in days away from work were documented, representing about one-third (30%) of all reported injury and illness cases. The Journal of Occupational and Environmental Medicine publication concluded that the Bureau of Labor Statistics (BLS) data was missing approximately two-thirds of WRMSDs reported cases, thus suggesting that the true statistic of reported cases of WRMSDs was about 1,071,000 (Workers Memorial Day Report 2009). The U.S. Department of Labor, Occupational Safety and Health Administration (OSHA) records have shown repetitive strain injuries as the most common and costly occupational health problem, affecting hundreds of thousands of American workers with an annual worker compensation cost of more than $20 billion (Kugel 2005; BLS 2006).

In Canada, the Alberta Construction Safety Association has reported that a high incidence of WRMSDs within the construction industry leads to frequent and costly occupational injuries and diseases resulting in lost-time claims (ACSA 2009; Spielholz et al. 2006; Schneider et al. 2010). Figure 2.7 and Figure 2.8 show the average cost and number of days lost (lost-time claims and cost) of WRMSDs for 2006-2010 for eight construction occupations. Figure 2.9 and Figure 2.10 show the average number of days away from work and the average cost of lost-time claims for MSDs in different residential construction occupations. WCB Alberta residential construction contractor statistics for 2006-2010 have recorded 285 claims of bodily reaction and exertion injuries, which were the second highest cause of lost time claims (35.8%), only surpassed by falls (36.64%) within the period (WCB Alberta 2011). Construction industry claims and injury statistics in British Columbia rank musculoskeletal injuries as the leading cause of work-related injury at a total of 35%, with 10,365 claims received in the period of 2006-2008, at a total cost of $144 million (WorkSafeBC 2008); sprains and strains accounted for over 40% of Lost Time Claims (LTC) reports between 2000 and 2009 for all industries (Figure 2.11). Similarly, Ontario industries rank WRMSDs as the top source of LTC (Figure 2.12). In Canada, the ACSA industries injuries report for 2008 shows that 93.7% of lost-time claims and 95.4% of disabling injury claims are caused by traumatic injuries and disorders. (Table 2.1 and Table 2.2, shows Alberta WRMSDs statistics. From Figure 2.8 it can be seen that for all construction trades over the years 2006-2010, bodily reaction injuries reported have been relatively constant, while over-exertion injuries have shown a more consistent decline. The reducing trend for over-exertion may be attributable to proactive measures taken to ensure weights are not above the recommended maximum limit as defined by the National Institute for Occupational Health and Safety (NIOSH) equation and guidelines. However, bodily reaction and exertion hazards which lead to cumulative trauma injuries have not received such proactive attention, thus remaining relatively constant over the same time period. Meanwhile, sprains and strains account for over 40% of LTC reports between 2000 and 2009 for all industries (Figure 2.11).

Table 2.3: WRMSDs Causal events - Alberta: 2008

Exposure Type or Event	% of Claimed injuries	% of Disabling injuries
Bodily Reactions/Exertion	**36.51%**	**39.50%**
Overexertion	17.97%	18.88%
Bodily Reaction	13.29%	14.99%
Repetitive Motion	2.88%	3.07%
Other bodily exertions	2.36%	2.56%
Contact with Objects	**30.36%**	**34.84%**
Struck by	15.93%	16.94%
Struck against	5.26%	6.83%
Rubbed or caught	7.05%	8.59%
Other contacts	2.12%	2.48%
Falls	22.06%	16.51%
Transport Accidents	4.60%	3.25%
Assaults, fires, etc.	0.54%	0.35%
Other exposures	5.94%	5.56%
Total	100.00%	100.00%



Source: CPWR - The Center for Construction Research and Training.
The Construction Chart Book. 2008. *Chart 16b, p16.* (BLS, USA)

Figure 2.6: BLS Statistics of WRMSDs for construction and all industries.

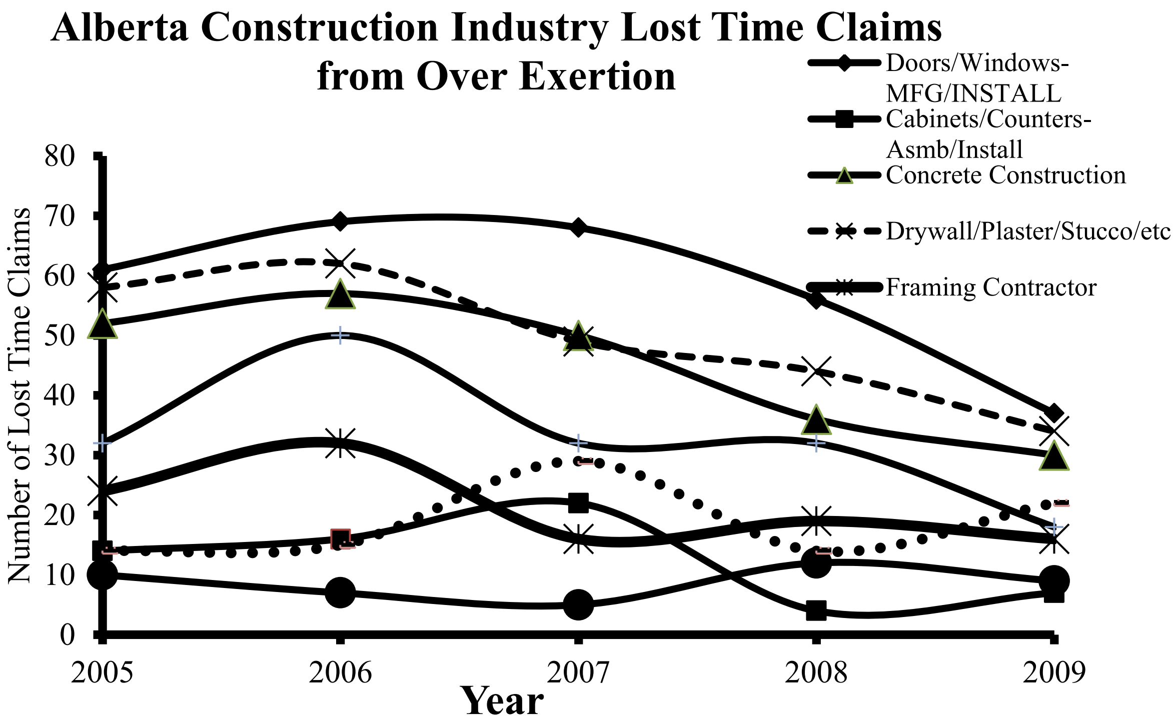


Figure 2.7: Alberta - Construction Industry LTC from overexertion.

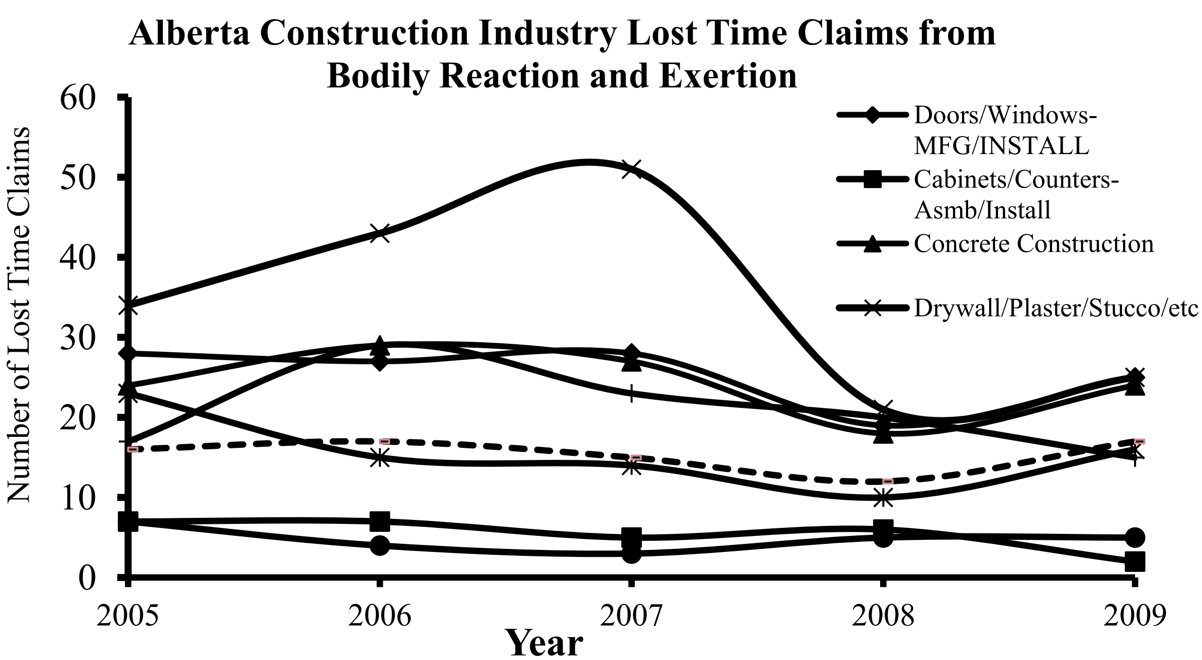


Figure 2.8: Alberta - Construction Industry LTC from Reaction and Exertion.

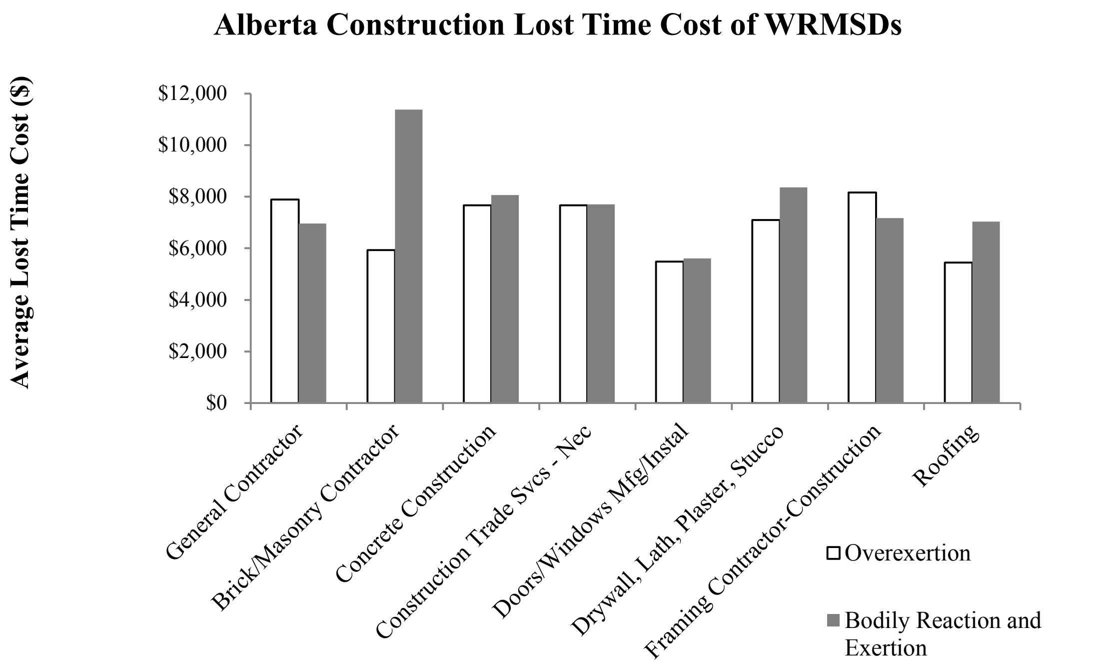


Figure 2.9: Alberta - Construction Occupations average LTC cost per WRMSD (2006-2010).

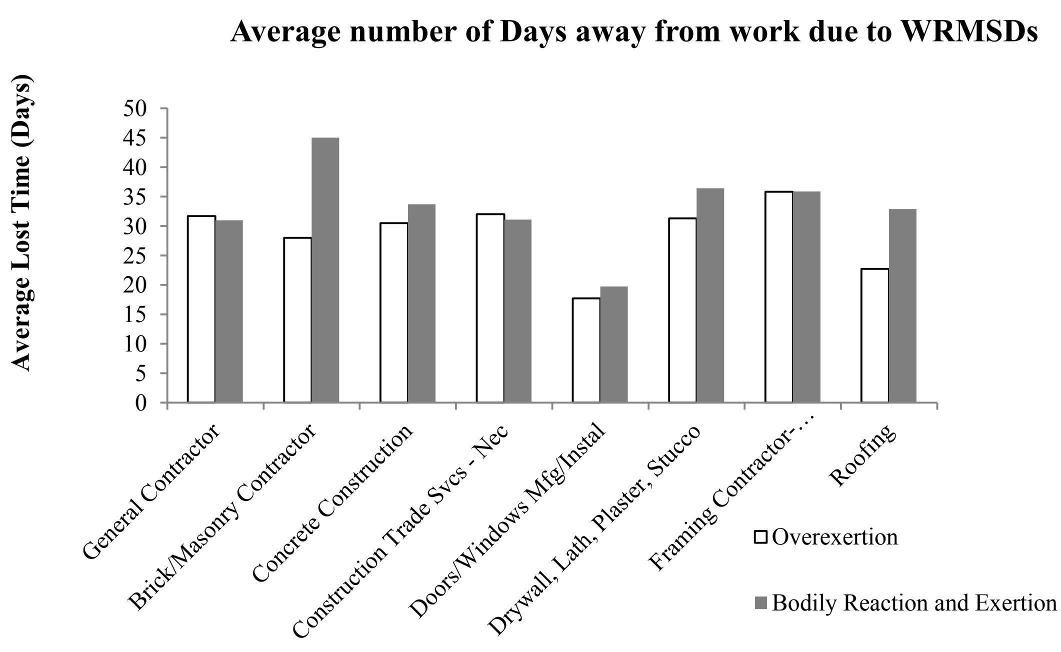


Figure 2.10: Alberta - Construction Occupations average number of days away from work due to WRMSD (2006-2010).

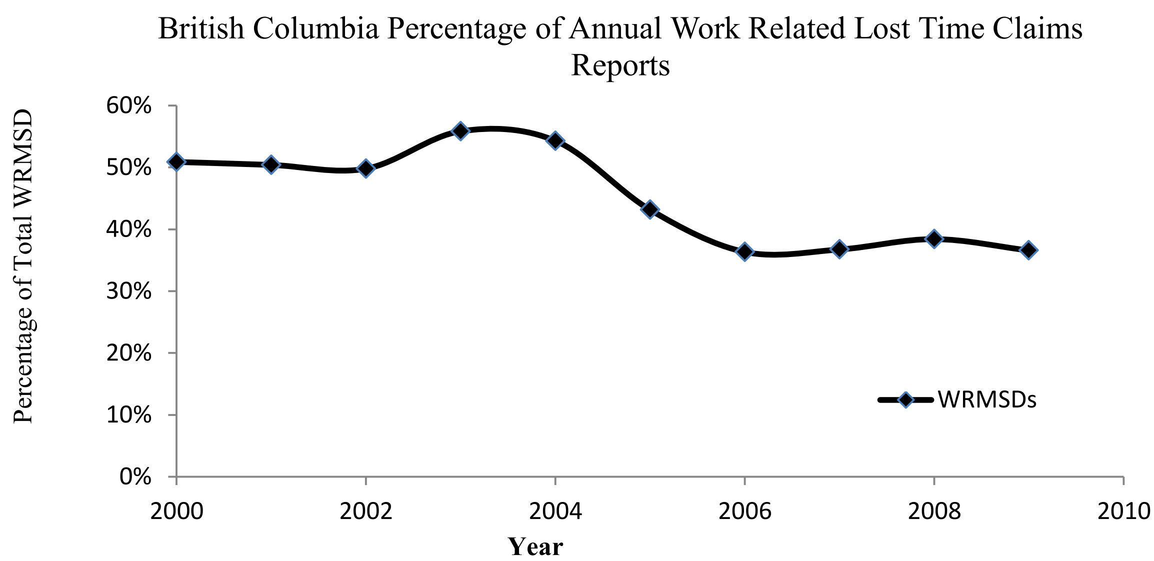


Figure 2.11: British Columbia – WRMSDs percentage of annual LTC (All Industries)

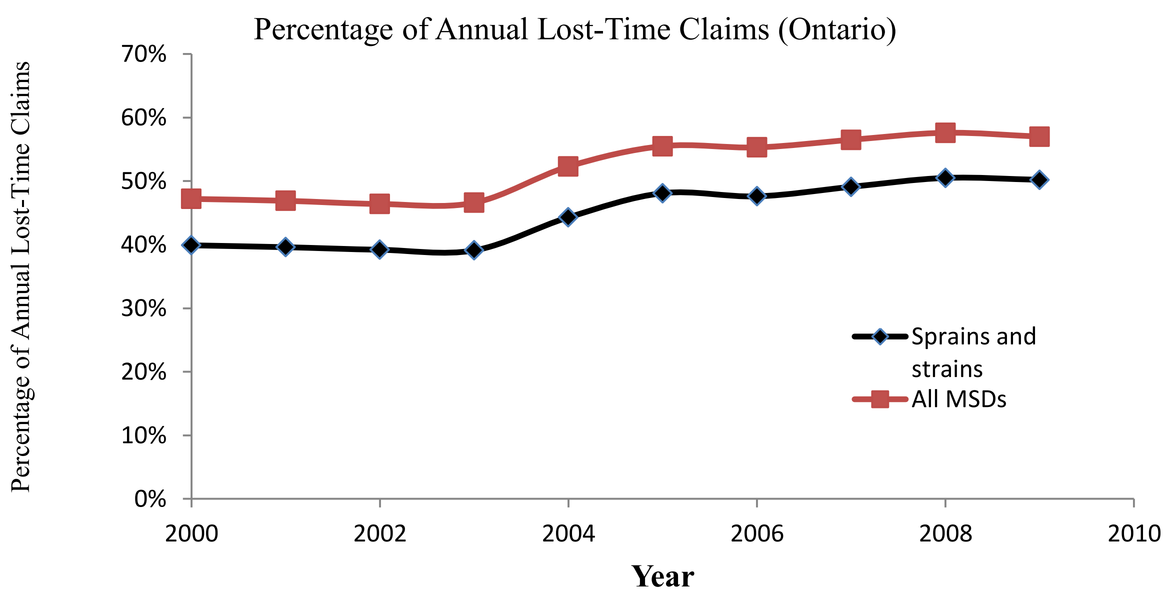


Figure 2.12: Ontario - Percentage LTC from Sprains and strains (2000-2009 - All Industries).

The U.S. Bureau of Labor Statistics results have indicated that the majority of traumatic and non-traumatic injuries are musculoskeletal in nature. Furthermore, about two-thirds of all occupational illnesses reported are traceable to exposure to repeated trauma from work (BLS 2006). This shows that more priority should be placed on assessing the risk from exertion and bodily reaction hazards.

2.2.2 Industry related Cost of Work-Related Musculoskeletal Disorders

The cost of work-related musculoskeletal injuries is difficult to assess, as it involves a combination of direct and indirect cost measures with short- and long-term impacts. Although practitioners, managers, and policy-makers within the construction industry are aware of the ergonomic risks associated with executing daily work tasks, the assessment strategy adopted for the most part merely lists the potential hazards of the specific task, and in a few cases possible control measures. The industry has failed to implement binding structures or policies to assess tasks on an ongoing basis in order to determine the instantaneous or cumulative effect of repeated risk exposure. Most of the focus with regard to construction safety is geared towards accidents, falls, and cuts. For these, most companies have well-defined mitigation and control policies in effect. Efforts aimed at mitigating or controlling ergonomic disorders have been outlined mainly in provincial and federal workplace health and safety legislation, codes, and national and international ergonomic guidelines. Some of the following cost impacts have been identified based on literature reviews and reports on WRMSD occurrence:

(i) Costs resulting from absence from work: The development of a WRMSD leads to a loss of productive work days as a result of worker absenteeism. Statistics from the Alberta construction industry between 2006 and 2010 show an average of 29 days of LTC (Figure 2.10). Also, overexertion and bodily reaction injuries have each resulted in average claims of $7000 during the same period (Figure 2.9). Lost time from work leads to schedule extensions, project delays, and the loss of experienced and skilled workers. As mentioned above, the adoption of safe ergonomic principles for work execution could potentially reduce worker compensation costs by 80 percent (Bernold and AbouRizk 2010).

(ii) Training and turnover costs: WRMSDs lead to a need either to employ new staff (which involves advertising, interviews, and training) or to train a replacement for the injured worker. In addition to treatment costs, work modification may be required for injured staff. Furthermore, employing new staff contributes to turnover costs by affecting project productivity (throughput and work quality) due to the inexperience of new hires.

(iii) Morale, quality of life and company's public image / safety reputation: WRMSDs affect the injured worker's ability to function optimally and may lead to permanent disability. This may result in the early retirement of an otherwise skilled worker. Frequent incidents of disorders lead to an increase in corporate insurance premiums, poor worker morale due to personal safety and health concerns, and potential damage to company reputation.

(iv) Productivity losses: WRMSDs increase the potential for loss in productivity and a reduction in quality (from increased errors due to injury). Longer hours and consequent overtime costs resulting from unplanned worker absenteeism due to injury lead to an increased workload for the remaining workers and may further increase the potential for further injuries. Statistics for LTC costs and productivity loss show billions of pounds in productivity costs in several European countries (Schneider et al. 2010). Coury et al. (1998) and Kumar et al. (2001) have also presented research showing the effect of fatigue and posture on productivity. Garg et al. (2006) have shown how repetition affects performance. Also, environmental factors have been shown to increase fatigue and lead to increased productivity losses (Chad and Brown 1995).

The adoption of proactive ergonomic practices has been shown to help maximize productivity by reducing worker fatigue and discomfort, reducing errors, and improving the bottom line up to 25% in the textile manufacturing industry. For instance, according to Microsoft (2011), the adoption of proactive ergonomic practices has led to a drop by more than 80% in WRMSDs, as well as a 40% reduction in workers' compensation costs. As with all construction and project-related initiatives, the impact of an initiative is greatest if factored in during the design of the project. This conforms to the American Society of Safety Engineers' *prevention through design* concept.

2.3 Literature review of Current/Existing Workplace Ergonomic Legislation

In Canada, the approach adopted to address WRMSDs and perform workplace ergonomic analysis varies from province-to-province depending on the given legislation and guidelines. There are four general approaches to workplace ergonomics which are adopted in Canada.

(i) Proactive Workplace Ergonomic Regulations.

The federal government, British Columbia, Manitoba, Quebec, and Saskatchewan have enacted proactive ergonomic regulations aimed at identifying and eliminating WRMSD hazards as part of the employer's responsibility. These legislations require the employer to assess all work activities that create a risk for WRMSD, implement control measures to eliminate or reduce the identified risks, inform the workers of such risks and provide protection, and monitor the effectiveness of any control measures. The legislations emphasize protecting employees from danger and employment-related hazards rather than on preventing injuries resulting from exposure (Legislation, Regulations and Guidelines 2010; Manager's handbook-Canada labour code-part II 2010).

(ii) Reactive Workplace Ergonomic Legislation

The province of Alberta, where this research was conducted, has a reactive legislation that is only activated if a worker reports to the employer what the worker believes to be symptoms of a work-related musculoskeletal injury. At this point, the employer is required to promptly review the worker's activities and those of workers performing similar tasks in order to identify causes of the symptoms, as well as to take corrective measures to avoid further injuries if the symptoms are deemed to be work-related (*Alberta OHS Code, Part 14, Sec. 211, 2009;* Legislation, Regulations and Guidelines 2010). This legislation requires the employer to assess the work conditions only after a worker has reported injury symptoms (such as stress, strain, or CTI symptoms); hence, no action is taken on behalf of the employer until a worker experiences and reports musculoskeletal discomfort. This places the workers in danger of prolonged exposure to CTIs.

(iii) Unenforceable Ergonomics Guidelines

Provinces such as New Brunswick, Newfoundland and Labrador, Nova Scotia, and Ontario have unenforceable guidelines, rather than ergonomic legislation. These guidelines list signs and symptoms of WRMSDs and common risk factors, suggest that employers establish an ergonomic program to recognize workplace risks, train employees, evaluate identified risks, establish control measures or contact ergonomic consultants to identify workplace risk factors, and encourage workers to participate in the health and safety program by reporting MSD symptoms or concerns early on (Legislation, Regulations and Guidelines 2010; Ministry of Labour 2010; Newfoundland Department of Labor Safety guidelines 2003; New Brunswick WHSCC pamphlet 2003; Nova Scotia Environment and Labour, OHS Division 2010; Legislation, Regulations and Guidelines 2010).

(iv) No Workplace Ergonomic Guidelines or Regulations

There are several provinces and territories with neither legislation nor guidelines on workplace ergonomic practices (Prince Edward Island, Yukon, Northwest Territories, and Nunavut) (Legislation, Regulations and Guidelines 2010).

In 1999, the U.S. OSHA proposed that industry employers establish an ergonomic standard which contained elements typical of successful existing ergonomic programs: management leadership and employee participation, job hazard analysis and control, hazard information and reporting, training, MSD management, and program evaluation. The inclusion of these elements would depend on the types of jobs being performed in the given workplace and whether or not an MSD covered by the standard had previously occurred. Employers would be required by the proposed rule to implement an ergonomic program for their jobs. This rule was signed into law in 2000, but was repealed by a ballot initiative in 2003 after concerted protests from the Chamber of Commerce and National Association of Manufacturers (Spognard and Ketay 2001; Spielholz et al. 2006). The European legal requirements regarding WRMSDs include international conventions and standards, European Directives, and European standards. These directives and legislations oblige the employer to take the necessary measures to ensure the safety and health of their workers in every aspect of their work (Schneider et al. 2010, Chapter 7).

2.4 State-of-the-art Research in Ergonomics and its Applications in Residential Construction

In order to ensure safe construction workplaces, periodical ergonomic risk assessments and proactive ergonomic practices need to be standardized. This will help identify and eliminate exposure to risk factors, ensure safer working conditions, and improve occupational health and safety (OHS) compliance, thereby reducing the occurrence of WRMSDs and, consequently, its adverse implications in terms of productivity and cost. Also, adopting an approach of prevention through design (PtD) early on in the task design phase will reap greater benefits. This underscores the need for integration of ergonomic assessment applications for daily residential construction work processes and tasks. Due to the multi-factorial nature of WRMSDs, many studies have been conducted in recent years providing a basis for ergonomic risk assessments.

The prevalence of WRMSDs has resulted in the development of various techniques for assessing work, such as Rapid Upper Limb Assessment (RULA, McAtamney and Corlett 1993); Rapid Entire Body Assessment (REBA, Hignett and McAtamney 2000); Ovako Working posture Analysis System (OWAS, Karhu et al. 1997); Quick Exposure Check (QEC, Li and Buckle 1998); University of Michigan 3D Static Strength Prediction program (3DSSPP, University of Michigan 2003); ERGOBUILD (Nussbaum et al. 2009); 3DSSPP/AutoCAD PC model (Feyen et al. 2000); and Ergonomic Workload Stress Index (EWSI, Chen et al. 1994). Some of these methods have proven generic applications (REBA, RULA, OWAS, QEC), while others may be applicable to specific industries or task types (ErgoCheck, ERGOBUILD, 3DSSPP, 3DSSPP/AutoCAD PC model). It should be noted at this point, that the degree of ergonomic risk largely depends on the nature and environment within which each task is executed. Each ergonomic assessment methodology is developed based on certain rationale and designed for specific work variables and conditions. This influences their risk scoring hypothesis and risk classification scheme, thus making them more applicable for assessing peculiar work conditions and exposure types. The result of this is a lack of consensus in risk classification for the same exposure condition (Motamedzade et al. 2011; Jones and Kumar 2007). Ergonomic assessment techniques can be categorized into four main groups: (a) checklists, surveys and reports, (b) observation-based methods, (c) computer applications, and (d) direct measurement methods.

2.4.1 Checklists, Surveys and Reports

The U.S. Department of Labor and Industries has presented ergonomic risk factors hazard assessment methods which have been widely adopted for the identification of ergonomic hazards and risks related to daily work tasks (Department of Labor and Industries, State of Washington 2000). This checklist can be adapted to the building construction industry's daily work tasks. Ergonomic analysis worksheets and checklists such as the Great American Insurance Group's ergonomic task analysis worksheet (2010) typically provide general activity-based risk classification for each task. This generates conclusions such as whether the task falls within the hazard or caution zone based on the duration or frequency of exposure and presence of single or multiple risk factors.

Reviewers can use these checklists to interview workers regarding the nature and task demands of the work. Most ergonomic research checklists and surveys target individual risk factors such as awkward postures, body segments, or certain injury types such as carpal tunnel syndrome or cumulative trauma injuries (Keyserling et al. 1992; Brinckmann et al. 1998). Groups and companies have modified the U.S. Department of Labor and Industries ergonomics checklist to fit their particular process. One such modified checklist, the "Ergonomics Task Analysis Worksheet," provides a method for identifying, evaluating, and eliminating/controlling ergonomic risk factors by observing several task cycles prior to making notes or drawing conclusions. For each task, a different level of risk factor is assigned (ideal, warning level, or take action). After completing the worksheet, the action plan to control or eliminate the risk factor can be determined, focusing first on tasks from the "Take Action" column (Great American Insurance Group 2010). The Ergonomic risk identification tool (CAPP and CPPI Ergonomics Working Group 2000) offers a step-by-step comprehensive ergonomic analysis methodology and general risk score for each risk factor. This method provides a general ergonomic risk analysis of work. It does not, however, account for the analysis of crucial construction-related risk factors such as the risk of exposure to hand-arm-vibration (HAV). Paper-based and electronic work task surveys used to assess the risks may be administered to the workers (self-reported surveys) or may be taken by a work supervisor, manager, or trained ergonomist. Workers' anecdotal records also fall within this category.

Some advantages of checklists, surveys and reports include that they are (i) straight-forward and easy to use; (ii) applicable to a wide range of work situations; (iii) applicable for assessing a large number of subjects at a low cost compared to other methods; and (iv) useful in identifying high-risk occupation groups for further analysis (Burdorf 1999).

Disadvantages include that (i) they require a large number of respondents from the assessed occupational group to participate in the survey in order for the data to be statistically acceptable; (ii) the large sample requirement may result in high data analysis costs; (iii) they require the availability of skilled personnel for analyzing and interpreting data and findings accurately; (iv) the level of worker literacy may affect the quality of responses to the survey (i.e., poor comprehension or interpretation of questions) (Spielholz et al. 2001); (v) worker perception of exposure to risk is often imprecise or biased (Balogh et al. 2004; Viikari-Juntura et al. 1996); and (vi) the level of reliability of this method is too low for use as a basis for designing interventions (Li and Buckle. 1999).

2.4.2 Observation-Based Methods

There are numerous field observation-based methodologies and frameworks which can be used to assess construction work. The most common and simple methodologies include (1) OWAS (Karhu et al. 1977); (2) REBA (Hignett and McAtamney 2000); (3) RULA (McAtamney and Corlett 1993); and (4) QEC (Li and Buckle 1998). The OWAS model, which has been designed primarily for use in medium to heavy assembly tasks in the steel industry, allows the analyst to record by category the posture load and force used. This procedure may be used in conjunction with random scheduling of observations to reflect the magnitude of risk. The REBA method assesses risks posed by static and repeated work postures on the upper extremities, legs, and muscles, and assigns a final risk score, risk classification, and recommendation (1 = negligible risk; 2 or 3 = low risk, change may be needed; 4 to 7 = medium risk, further investigation, change soon; 8 to 10 = high risk, investigate and implement change; 11+ = very high risk, implement change). The RULA tool, which is a posture, force and, muscle use assessment tool, is applicable only to the assessment of risk factors of upper limbs (it also includes an assessment of coupling). The QEC developed by Li and Buckle in 1998 and later enhanced by David et al. (2003) is an ergonomic assessment technique which groups the body into four regions: back, shoulders/arms, neck, and hands/wrists. The observed group is rated with two to three step scales using fuzzy logic. This method identifies risk based on the task weights, durations of tasks, hand force, visual demands, driving force, use of vibrating tools, work pace, and stress. It produces both individual risk scores and classifications for each body part. It determines an overall risk score by adding scores from all the body groups and dividing the sum by the maximum score (176 for manual material handling tasks and 162 for others). Satisfactory exposure is assigned for scores <40% of maximum, 41% -50% (further investigation, changes recommended), 51%-70% (high risk), above 70% (very high risk, requiring immediate intervention). These correspond to four risk levels, 1-4: low, moderate, high, and very high.

The commonly used observation-based methodologies provide a quantitative framework for ergonomic task risk analysis with a risk score. The major shortcoming of these methods is the limited or partial nature of the risk analysis. Most of these methods focus on analyzing work postures, and to a lesser extent work rate (repetition) and force/static loading. The contribution of other ergonomic risks, such as hand-arm and whole body vibration, the effects of environmental factors such as heat and cold, contact force and psychosocial factors, are usually not accounted for. These methods usually provide the data and framework used to design computer-based ergonomic analysis and decision support models. Also available are a range of video-based observational techniques (Video analysis, ROTA, TRAC, HARBO, PEO, PATH, SIMI Motion, Biomechanical Models, tri-axial based video models) used to identify postural variations for highly dynamic activities. However, video-based assessment methods are not very suitable for onsite assessment at the workplace (David 2005).

Due to these characteristics, observation-based techniques possess both advantages and disadvantages which must be taken into consideration during the technique selection process.

a) Simple Observation-based Techniques

The advantages of simple observation-based techniques include that they (i) are inexpensive and practical for use in a wide range of workplaces; (ii) are the most suitable techniques for assessment of static postures and repetitive (simple) tasks; and (iii) offer good applicability for a wide range of risk factors (McAtamney and Corlett 1993; Waters et al. 1993; Occipinti 1998; Li and Buckle 1999; Hignett and McAtamney 2000; Monnington et al. 2003).

Its disadvantages include that they (i) may be subject to inter- and intra-observer variability when choosing between different exposure levels (David 2005); (ii) have limited epidemiological data to support the scoring system used as the basis; and (iii) in most cases the scoring system is highly hypothetical.

b) Advanced Observation-based Techniques.

The advantages of these techniques include: (i) their use of real-time recording of workers' postural variations; (ii) their ability to analyze several joint segments simultaneously; (iii) their ability to determine dimensions such as distance of movement, angular changes, velocity, and acceleration; and (iv) their suitability for recording and analyzing simulated tasks.

Their disadvantages include that (i) they are very expensive; (ii) they require extensive technical support from highly trained staff; (iii) their operation may be too time-consuming for use on construction sites; and (iv) they are not well suited to onsite assessment at the workplace (David 2005).

2.4.3 Direct Measurement Methods

Direct methods include all techniques which allow measurements of the worker's risk exposure and musculoskeletal activity while the tasks are being executed. This is usually done by attaching different types of sensors directly to the body of the worker. This includes the use of simple hand-held devices which measure a range of joint motions as well as the use of goniometers for continuous measurement of joint motions during work. These methods facilitate the measurement of wrist angles, forearm rotations, hand and finger movements, grip pressure, body postures, velocity and acceleration (Bernmark and Wiktorin 2002; David 2005). Others include devices which allow for synchronous recording and computer analysis of myoelectric activity (EMG) to estimate muscle tension and fatigue (Wells et al. 1997; Merletti and Parker 1999; David 2005). Equipment such as LMM, Electronic goniometry, inclinometers, body posture scanning systems, EMG, force movement, and CyberGlove fall within the scope of direct measurement methods (David 2005). A major advantage of these methods is the provision of large quantities of highly accurate data for a range of exposure variables.

Their disadvantages include that (i) attachment of sensors directly to the worker's body may result in discomfort, and may necessitate work modification; (ii) it can be costly to purchase, set up, operate, and maintain the needed equipment; and (iii) they require highly trained and skilled technical staff to operate equipment.

2.4.4 Computer-based Applications for Ergonomic Analysis

Computer-based models are widely applied in the ergonomic analysis of the workplace. These are mostly based on frameworks and methodologies founded on a combination of observation-based, checklist, and artificial intelligence methods.

Computer-based observation models: Some of these include the OWAS work posture analysis, RULA, and REBA models, which are based on the observation-based methodologies discussed in Section 2.2.2 above. Some observation-based computer models, such as ERGOBUILD

(Nussbaum et al. 2009), were designed to provide early assessment of both ergonomic and productivity concerns and are intended to be applied on residential construction projects using panelized walls. The model provides design schedules, construction plan alternatives, and simulation animations of the construction process by using the available number of workers, available time for work, and maximum acceptable ergonomic risk as input. The NIOSH developed the lifting equation and revised lifting equation for assessing and controlling manual handling ergonomic risks.

Biomechanical Models: A central ergonomics theory published in the scientific literature is the evidence of the biomechanical origins of musculoskeletal injuries (Kumar 2001). The estimation of muscle forces and power exerted or required for executing various activities is necessary in assessing the potential development of work-related musculoskeletal disorders (WRMSDs). This is because muscles generate and subject other tissues to significant stresses due to over-exertion or cumulative exertion (bodily reaction). Basic concepts of static and dynamic equilibrium can be applied to different segments of the human musculoskeletal system using free body diagrams to estimate muscle forces generated across the joints and tissues. Biomechanical assessment techniques are applicable for both static and dynamic assessment of physical risk factors; these use the concept of inverse dynamics to determine the forces, torques, and stresses at joints and segments and also solve force distribution problems in muscles at each joint or body segment. Biomechanical assessments are based on the knowledge that joints stabilize the segments and sustain external loads by engaging muscles and generating torques. Thus, analyzing the stresses on individual joints will be beneficial in determining joint strength and energy loss during a continuous working process (Ma et al. 2009). Biomechanical applications allow for the calculation of torques developed by muscles pertaining to the body's joints during infrequent lifting tasks, such as are prevalent in construction operations. This is important in the determination of the strain on muscles, bones, and tissues generated by external loads on body segments under various working postures. Body segment dimensions, their volumes and mass properties for diverse populations of workers can be calculated from anthropometric data. Kinematic chain models of linked body segments allow for the prediction of total body capability, such as lifting tasks in terms of body segment capabilities. Published conclusions from various research experiments show that the capacity for infrequent lifting is a combined function of both the individual's muscle strength and the strength of various body structures, especially the spine. These studies have conclusively shown that lifting under certain postural conditions is limited more by lumbar stress than by muscle strength. Also, modelling of lifting activities has shown that large moments are created in the trunk area during lifting, and that this is proportional to the distance of the object from the body (Waters et al. 1993). Biomechanical models have been used to estimate in vivo compressive forces on the L5/S1 intervertebral joint and disc. Chaffin (1969) developed a biomechanical model (static sagittal-plane model (SSP)) for assessing static lifting in the sagittal plane (Figure 2.13). This model predicted compressive forces at the lumbosacral disc based on two sources of internal forces (the extensor erector spinae muscle and the abdominal cavity pressure) to resist the external load moment during lifting.

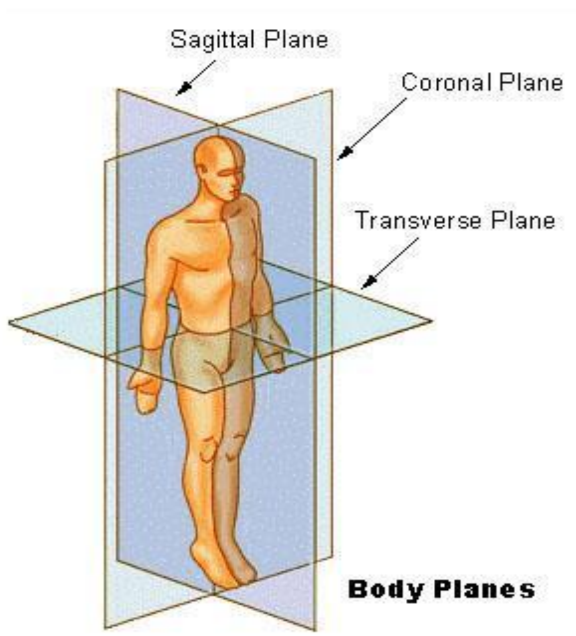


Figure 2.13: Planes of motion

(http://www.warriorfitnessworld.com/articles/2007/02/training_101_planes_of_motion.php)

Biomechanical assessments of forces and loads result in a simplification of actual (physiological, anatomic, and anthropometric) characteristics to fit the methods and techniques derived from the mechanics. It should be noted that anthropometrics is still a developing science. Although applications of biomechanics result in limitations regarding the completeness, reliability, and validity of anthropometrical procedures, they do result in research outcomes which offer unique insight that would not have been generated using traditional approaches. However, the limitations at play when drawing research conclusions must be acknowledged. Ayoub and Wolstad (1999) identified the need for an understanding of the cumulative effects of work tasks performed over days, years, and even an entire working career, as this would help prevent WRMSDs. In this regard, the development of models capable of considering dynamic components of lifting tasks, possible antagonistic muscle forces, passive tissue loading, and three dimensional loading characteristics of the muscles would be more realistic (Waters et al. 1993). As part of this study, a body segment-based biomechanical model will be developed which is adaptable for assessing the moments and stresses resulting from residential construction work. This model will be flexible for adaptation to construction process modelling and simulations.

Visualization Applications: Visualization often refers to highly visual 3D simulations of a real or imagined environment. This is often developed on a computer using software such as Bryce, Extreme 3D, Ray Dream Studio, trueSpace, or 3D Studio MAX, and may be used to present information, or for educational, gaming, or training purposes. Visualization provides a detailed model of the studied process, thus making a proposed concept clearer and easier to comprehend. In construction, visualization is a popular technique which has been used extensively to communicate proposed designs, facility layouts, and process performance. It has been applied to facilitate decision-making for tower crane operations of modular buildings, production line assessments, and earth-moving (tunnelling) operations through an integration with project information, schedules, logic, or other desired variables (Al-Hussein et al. 2006; Kamat and Martinez 2000). An integration of visualization and biomechanical techniques results in the development of digital human models.

Digital Human Models: Digital human modelling provides visualization information about various postural and material handling operations. These digital models integrate traditional posture analysis techniques such as RULA, OWAS, RNLE and biomechanical assessment techniques into the visualization tools in order to simulate the work scenario. Popular digital human modelling programs used for proactive assessment of ergonomic risks from work include Siemens Tecnomatix Jack, Santos Ergoman, 3DSSPP and CATIA (Ma et al. 2009). Digital human modelling (DHM) tools have been introduced in industry to facilitate a faster and more cost-efficient design process. This technology allows ergonomists and engineers to perform virtual builds, and the rapid adoption of virtual tools presents an opportunity to integrate considerations of ergonomics into the early design stages (Mathiassen et al. 2002). The tools are applied in the design, modification, visualization, and analysis of human workplace layouts and/or product interactions. Digital human models have been developed and applied towards assessing work conditions, including in the aerospace and military sectors (Ma et al. 2009). The focus of research within ergonomics simulation has primarily been on improving the simulation tools with more enhanced functionality, resulting in better and more accurate posture and motion algorithms and biomechanical models (Chaffin 1969; Bhatti et al. 2005; Abdel Malek et al. 2006). Several studies have been carried out to validate different DHM tools for ergonomics in vehicle evaluation (Loczi et al. 1999; Nilsson 1999; Vogt et al. 2005). All these studies show that the outcomes of the different tools are fairly accurate. Gill and Ruddle (1998) presented an early work describing the general benefits of the use of a DHM tool for ergonomics assessments.

Digital human simulation models and tools generate and visualize the work environment and loading conditions at each joint and muscle, and then use the integrated analysis technique to execute an ergonomic assessment of the work. Existing systems mostly consider static loading and posture scenarios, thus rendering the results inaccurate. While some DHM tools only report instantaneous assessments, others, such as the Tecnomatix Jack program, have the capacity to accumulate the risks of different activities over a typical work period (such as an 8- or 10-hour working period). DHM tools are complex, and their successful use requires good expertise in different fields. It is necessary to know ergonomics but also to have CAD skills as well as a detailed knowledge of the various features of the product being designed/evaluated (Lockett et al. 2005).

Biomechanical and digital human models such as the 3D Static Strength Prediction Program (3DSSPP, University of Michigan 2003) offer both postural and biomechanical load analysis functionalities and methods. The 3DSSPP/AutoCAD PC model for proactive ergonomic analysis of the biomechanical risk for injury based on proposed workplace design (Feyen et al. 2000; Ma et al. 2009) couples the use of the 3DSSPP and AutoCAD interface for ergonomic analysis. Dickerson et al. (2007) have presented a mathematical musculoskeletal shoulder model for proactive ergonomic analysis. The model includes kinematic and kinetic effects, population scalability, geometric realism, an empirical glenohumeral constraint, and integration with digital ergonomics analysis software tools. This unique combination of features in a single model was explored by examining both experimental and simulated data with the developed analysis tool.

Also, Siemens product lifecycle management (PLM) software, Tecnomatix Jack (mentioned above), offers a human modelling and simulation platform with toolkits providing human-centered design tools for performing ergonomic analysis of virtual products and virtual work environments. The Tecnomatix Jack program facilitates the assessment of multiple ergonomic risks factors, including metabolic cost, comfort assessment, and fatigue, using multiple anthropometric databases. Ergonom, a computer-aided model, was developed by Swat and Krzychowicz (1996) to diagnose machines or other technical objects for work posture stress. This model evaluates loads resulting from workplace postures dominated by standing and walking positions, estimating the pre-existing load during the design stage. It consists of three computer programs which allow for the description of postural zone boundaries (heights) for comfortable manual operation as well as for ergonomic diagnosis of a machine or other technical object early in the design stage, and is a capable system for executing working posture evaluations for the ergonomic testing of machinery prototypes (based on the analysis of full data on the postural activity of the operator). The model allows the designer to test various manual controls and work area arrangements in order to obtain an ergonomically satisfactory solution. It also makes possible the pre-purchase testing of imported machines with regard to the anthropometrical dimensions (i.e., body dimensions—size, weight, height) of the national operator (worker) population based solely on technical documentation (Swat and Krzychowicz 1996). Biomedical and biomechanical analysis equipment has the capability of measuring specific muscle load magnitudes, indicating the increase in risk for the body part observed. The results from the measurements can then be incorporated into digital ergonomic analysis tools (Dickerson et al. 2007). This method has the potential for proactive ergonomic hazard analysis, as it offers options of workplace simulations magnitude / dose pattern and recovery processes of the isolated body part and, in turn, shows the shape of the exposure-response relationship. However, the endpoints are typically short-term responses that may or may not represent events on the causal pathway to developing clinical syndromes/disorders (Punnet and Wegman 2004).

Artificial Intelligence Models: Computer-based models also include models which use Artificial Intelligence Methods as quantitative frameworks. These include specialized ergonomic analysis models based on expert/cognitive models, and methods such as fuzzy-based systems. A Fuzzy-based system captures and adapts industry experts' knowledge and experience for workplace safety risk evaluations. These systems use subjective information from linguistic terms in defining the universe of discourse in which each risk factor membership is determined. It subsequently determines the degree of risk based on the perceived risk exposure-response relationship. The fuzzy set theory was applied to develop and model the ergonomic workload stress index – EWSI (Chen et al. 1994) to predict the existence and level of ergonomic workload stress. The main challenges associated with this method are the task of fitting fuzzy connective and logical operators to human judgmental data in the design and evaluation, as well as the vagueness of natural language. The application of fuzzy technology to ergonomics and for modelling injury risk has thus been limited (Leondes 1999). Other applications of fuzzy logic to work-based ergonomic risk assessment include fuzzy linear regression models for assessing CTDs (Bell and Wang 1997), and the development of an expert cognitive approach to evaluate physical effort and injury risk in manual lifting (Yeung et al. 2002). Computer-based models are predominantly developed to provide decision support functionalities.

Discrete Event Simulation Application: Simulation is an abstraction of reality which presents process interaction, sequence, and which supports numerical and logical computations. The information presented can be used to assess multiple "what if" scenarios (Moghadam et al. 2011). This powerful technique, which reduces the time required and the need for visual assessment, computation, and model development, is often used to support decision making in construction management. Accuracy in modelling the process can assist in the development of better alternatives and optimization of resources. Common construction simulation techniques include Cyclone - CYCLic Operations Networks (Huang and Halpin 1994) and Special Purpose Simulation, (SPS, now "Simphony") (Hajjar and AbouRizk 1999; 2002).

Traditional ergonomic assessment methods have to be performed on site. This is time-consuming and, often, cost-intensive. This also constitutes a reactive approach and thus the assessment of the impact and feasibility of recommendations/alternatives will be costly and may disrupt work, thus posing challenges to productivity. There is also a time delay for analysis and interpretation of the data collected during the assessment (Ma et al. 2009). Applying discrete event simulation for ergonomic assessments thus presents immense opportunities for a wide variety of construction scenarios.

The Revised NIOSH lifting equation: NIOSH set up a committee to review the then current literature and recommend guidelines and criteria for defining lifting capacity for asymmetrical lifting tasks. The recommended limits represent a load value that nearly all healthy workers could perform over a substantial period of time (up to 8 hours) without developing lifting-related low back pain. Several criteria were used to develop the lifting equation in 1985 and the revised lifting equation in 1991, since each task imposes different biomechanical and physiological requirements on the worker. This results in different limiting factors for each task (Waters et al. 1993). The revised NIOSH lifting equation is a comprehensive assessment tool designed to assess biomechanical, psychophysical and physiological parameters in order to identify the MSD risk resulting from the given manual material handling requirements of the job. The equation is thus based on these three parameters.

The revised NIOSH lifting equation uses the biomechanical criterion/approach to model the mechanical stresses placed on the musculo-skeleton during lifting in order to assess and recommend safe lifting practices. Biomechanical methods model the human skeleton as composed of mechanical links and joints in series. The external forces needed to perform work and the internal forces resulting from muscle contraction are modelled in order to estimate the mechanical stresses developed. Manual material handling assessments usually focus on the analysis of compressive forces on the low back. The biomechanical criterion thus hinges on three basic conclusions:

(i) The greatest lumbar stress during lifting occurs at the L5/S1 (fifth lumbar and first sacral) joint.
(ii) The critical stress vector at the L5/S1 joint is the compressive force.
(iii) A compressive force greater than 3.4kN signifies increased risk.

The basis of these conclusions has been supported in NIOSH documents (NIOSH 1981, 1994) and in epidemiological studies by Garg, Chaffin, and Herrin (1978) and Ayoub and Woldstad (1999). The revised lifting equation (Equation 2.1 and Equation 2.2) provides methods for evaluating asymmetrical lifting tasks, lifts of objects with less than optimal hand-container coupling, and for a range of lifting durations and frequencies, and it serves to determine the recommended weight limit for each work scenario.

$$RWL = LC \times HM \times VM \times DM \times AM \times FM \times CM \qquad \text{Equation 2.1}$$

$$LI = LW/RWL \qquad \text{Equation 2.2}$$

(Where: LI= Lifting index, <1-safe, >3- change). RWL= Recommended weight limit, LW = Load weight, LC = Load constant (Equal to 51lbs), HM, VM and DM are the horizontal, vertical, and distance multipliers, respectively. AM, FM and CM are asymmetry, frequency, and coupling multipliers, respectively. Each multiplier has a range between 0 and 1).

A lifting index greater than 1 is considered as posing an increased risk for low pain for some fraction of the workforce. This equation assumes that lifting and lowering tasks present the same risk. The basis of selection of each of the three criteria has been discussed in Waters et al. (1993).

Various quantitative assessment models for manual handling tasks have been developed based on NIOSH recommendations and epidemiological research conclusions.

The advantages of computer-based techniques are that (i) they are flexible and sometimes easy to use; (ii) the applications are practically limitless (depends on the skill and scope desired); and (iii) they are suitable for proactive assessments.

Disadvantages include that (i) the validity and accuracy is dependent on the skills of both the designer and the user; (ii) the model design and operation cost may be high depending on the complexity and functionality desired and the range of application; and (iii) a high level of expertise is required to execute this type of analysis.

In spite of their wide acceptance, none of the aforementioned models integrate hand-arm vibration (HAV) exposure analysis to their list of ergonomic risk variables. HAV exposures are usually executed as a stand-alone risk assessment process. Few methods discussed integrate the effect of environmental and organizational factors such as temperature, work breaks, and rotations/exercise. Furthermore, none of the literature reviewed nor the state-of-the-art models currently applied in engineering, ergonomics, or health presents an application of discrete event simulation modelling for ergonomic risk analysis.

2.5 Relationships between ergonomics exposure risk, worker productivity, and efficiency

In spite of increased investment in the automation of construction plants and processes, manual handling is still prevalent in construction operations. This is due to the increased demand for customized products and the human ability to learn and adapt quickly (Ma et al. 2009). Manual handling assessments allow for investigation of the man-task-environment. Manual handling disorders such as back injuries represent a major percentage of the WRMSDs reported by the construction industry due to the fact that workers usually have to lift, carry, hold, and lower loads that vary in location and weight throughout the workday (Ayoub and Wolstad 1999). The design of the task determines the posture under which the task is performed. The assessment of manual handling tasks helps in the determination of safety guidelines for workers based on a determination of task demand and worker capacity. WRMSDs directly affect the cost (whether direct compensation for injured workers or LTC costs) and productivity of a project and thus should be prevented. Industrialization of the construction process through offsite manufactured building panels (panelization) or modular construction is becoming increasingly popular, recognized as an environmentally-friendly process with opportunities for productivity enhancement and waste reduction at competitive costs. The residential construction industry faces the ongoing challenge of increasing productivity while assuring the safety of its workers. Since construction processes are substantially variable and usually have irregular activity durations (Forde and Buchholz 2004), increasing productivity may lead to pressure to perform work tasks more quickly, thus posing an increased risk of exposure to "manufacturing type" ergonomic risks and WRMSDs (Kim et al. 2011). Ergonomic assessments are thus necessary, as improvements in work productivity and reductions in exposure to ergonomic risks can be achieved by redesigning the production process, facility layout, and material handling processes based on research recommendations.

2.5.1 Human factors and productivity

Human factors as they relate to productivity, though not given sufficient attention, strongly impact jobsite productivity and influence project success. Improved health and safety practices and design help to reduce injuries/disorders, thus minimizing LTCs and improving productivity. A safe and healthy worker is a productive worker, as safety and health results in a comfortable working environment, hence improving worker motivation (Dozzi and AbouRizk 1993).

A worker's ability to perform physical (manual handling) tasks is dependent on their capacity to exert muscular strength. The worker's productivity is also affected by the efficiency of task performance. The operation of equipment also requires the exertion of muscular forces and torques (Mital and Kumar 1998a,b). Muscle fatigue involves the failure of the muscle to maintain a required or expected force or a loss of maximal force-generating capacity during exercise (Encyclopedia of the Neurological Sciences 2003). Daily work tasks expose the musculo-skeleton to varying degrees of stress which may lead to fatigue and injury. Construction operations usually involve repeated exposure to multiple ergonomic risk factors, manual material handling, and awkward postures which may expose the worker to cumulative muscle stress and fatigue in a typical working day. The time at which the point of fatigue is reached determines the duration within which the worker can maintain a steady state of energy for work. In this context, energy is defined as a measure of the ability of a body or system to do work or produce a change. Muscles have been shown to demonstrate cumulative fatigue proportional to the degree or duration of exposure to continuous loading due to work execution. Fatigue results in a reduction in available muscle energy, which also presents a risk of reduction in accuracy and thus increased potential for other forms of workplace accidents and errors, leading to rework, reduced efficiency, and injury. It is thus important to understand the relationship between the degree of ergonomic risk exposure, worker productivity, and efficiency as well as the relationship between muscle fatigue and muscle strength to aid in the design of work processes (durations of exposure to muscle stressors) in order to maintain optimum worker performance. Improving productivity is a major concern for any profit-oriented organization, as representing the effective and efficient conversion of resources into products and determining business profitability. Productivity, it should be noted, is generally defined as the ratio of outputs to inputs (Wilcox et al. 2000). Muscles in different parts of the body experience fatigue differently with respect to the type of risk exposure which impacts the worker's performance (Garg et al. 2006; Kumar et al. 2001; Straker et al. 1997; Coury et al. 1998). Other risk factors, such as heat and cold, have also been shown to influence worker fatigue (Chad and Brown 1995). The combination of various risk factors further increases the rate of fatigue. Overexertion and bodily reaction injuries may thus be sustained by the worker if the muscle is fatigued and thus is unable to generate sufficient strength, or if the required force/torque is higher than the Maximum Voluntary Contraction (MVC) force of the individual, a case which may lead to an overloading of the muscle-tendon-bone-joint system (Mital and Kumar 1998b). The MVC is a measure of strength which can be measured as maximal muscle force or moment around a joint. The ability to exert this force is influenced not only by structural factors (cross-sectional area and muscle fibre type), but also factors such as brain activation (Fakunaga et al. 2001). Since muscle strength returns after sufficient rest/recovery, and the degree of fatigue is directly proportional to the available muscle strength (% of MVC), work designs which reduce muscle fatigue would improve worker efficiency and productivity while reducing the incidence of WRMSDs. This knowledge is useful for the design of work tools and rest/recovery cycles. Understanding the behaviour of the human musculoskeletal system and muscular strength for various body segments is also necessary for the prevention/reduction of WRMSDs. Likewise, an ability to determine the degree of local muscle fatigue and required relaxation allowances is important for the determination of thresholds for safe task and activity durations and rates (Price 1990). Such thresholds would provide guidelines for establishing organizational factors during the design of construction work tasks. Various static and dynamic muscle fatigue models have been developed in the existing research, and their success presents relationships that will be useful in designing appropriate work recovery interventions based on muscle strength-fatigue relationships (Ma et al. 2009; Price 1990). Ergonomic interventions have three main advantages: they (1) minimize fatigue; (2) maintain or increase productivity; and (3) minimize health effects (disorders).

2.5.2 Muscle Strength

Muscle strength is a primary measure of an individual's physical capability, which permits a person to exert force or sustain external loading safely. This is usually the maximal amount of force that can be generated by a specific muscle or muscle group in a single contraction. Various strength tables, models, and regulations have been developed and are used as a basis for setting the limits of strength for different worker populations and anthropometry under a variety of scenarios (Mital and Kumar 1998a,b; Kumar 1995). The term muscle strength is often confused in the literature. It may refer to either:

(i) tension (force) within a muscle
(ii) internal transmission of muscle tension (force) via limbs; or
(iii) external exertion of force or torque via a body segment to an outside object.

Muscle strength is the maximal tension or force that a muscle can develop voluntarily between its origin and insertion. This shows that individual muscles should be considered in local muscle fatigue assessments. Internal transmission refers to the means by which muscle tension or force transfers inside the body along links and across joints as torque to the point of application to a resisting object. Where the internal transmission path of torque traverses several link-joint structures in series, each transfers the arriving torque to the next link-joint until resistance is met, usually where the body interfaces with an outside object (Karwowski and Marras 2003). This is more complicated in dynamic conditions than in static cases because of the changes resulting from motion due to muscle acceleration and deceleration. Body (segment) strength is the force or torque that the segment can apply to an object external to the body. The segment may be hand, elbow, shoulder, back, or foot. The quality and magnitude of force or torque the body segment can transmit to an external object is dependent on the mechanical and physical conditions of either the:

- body segment employed (hand, elbow, shoulder, back, or foot);
- direction of force (torque vector);
- needs for caution and control in task execution; or
- static or dynamic exertion

These factors need to be considered by the ergonomist or designer in task design (Karwowski and Marras 2003).

Research publication by Mital and Kumar in 1998 shows the results of an extensive and comprehensive study of human muscle strength determinations and measurements. The muscle strength guidelines developed from this study clearly highlights the scope, assumptions and limitations of the study (Mital and Kumar 1998a; Mital and Kumar 1998b). From this study, human muscular strength has been classified based on the effort applied or type of application. For the effort criterion, human strength is classified as either static or dynamic. Static strength applies to muscle force or torque capacity determined by measuring the maximum voluntary isometric exertion (body segment is stationary; displacement=0). Dynamic strength, on the other hand, considers the displacement of the body segment during task execution. Since in all cases of construction work the body segments of the worker are in motion, considerations of static strength measures are not applicable and thus will not be given further attention within this research. Based on the type of application, muscle strength is classified as either static functional strength or dynamic functional strength. This pertains to the characteristics involving the motions of the functional body segments during work. Only dynamic strength will be considered further within this study.

Dynamic Muscle Strength

Mital and Kumar (1998a) further classified dynamic muscle strength as either isotonic or isokinetic strength. Isotonic muscular strength pertains to muscle action which produces a constant muscle force. However, biomechanics shows that the lever arm changes throughout motion, such that the force developed by the muscles will be changing and thus non-isotonic. Isokinetic muscular strength/exertion refers to the condition of constant angular velocity or force at the joints or a constant rate of shortening or lengthening of muscle. This measures the worker's maximum voluntary contraction when the segments move at a constant speed. Dynamic functional strength has also been classified by Mital and Kumar (1998a) as either iso-inertial muscle strength (the person's ability to overcome the initial static resistance and move freely), repetitive dynamic strength (the isokinetic or psychophysical dynamic strength with the frequency of exertion accounted for in the strength measurement), psychophysical muscle strength (based on the person's perception of maximum acceptance level of force in that application) and the simulated job dynamic strength (the dynamic isokinetic or psychophysical muscle strength measured while simulating the task performance). The simulated job dynamic strength is usually based on the posture and speed of motion. The iso-inertial and psychophysical muscle strength will not be investigated further nor applied within the context of this research. Figure 2.14 shows the discussed muscle strength classification. The shaded terms represent the areas within the scope of this thesis, while the non-shaded terms will not be investigated further or applied to this research.

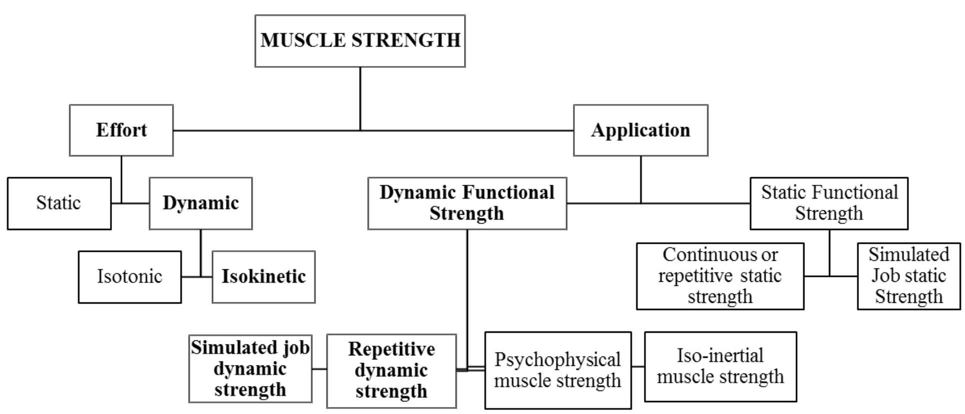


Figure 2.14: Muscle Strength Classification

Mital and Kumar have compiled a comprehensive collection of human strength tables for various joints and segments under different loading/stress scenarios for dynamic strength determination. Table 6 from their study shows the isokinetic dynamic lift strength, dynamic back extension strength, and elbow flexion strength. The mean peak and average isokinetic stoop and squat strength are presented in Tables 11 and 12, respectively, for the sagittal, 30° lateral, and 60° lateral planes for males and females). Based on the same study by Mital and Kumar, Table 2 shows declining muscular strength capability with age for both male and female working populations. Appendix B presents strength tables and model equations applied within this study, as adapted from Mital and Kumar (1998a,b) for various working scenarios.

Factors affecting human strength

Human strength is determined by one or a combination of the following factors: age, gender, posture, reach distance, arm and wrist orientation, speed of exertion, duration, and frequency of exertion. The peak strength age range is between 24 – 29 years, and it drops to about 71% by the age of 65 years. There is also a difference in the strength of women compared to men of the same age bracket (Mital and Kumar 1998a Table 2). The isokinetic strength is shown to be significantly affected by the adopted posture; this can vary from no force exertion capacity to considerable force. Also, greater force can be exerted in a standing posture than while seated. The reach distance determines the lever arm and thus the torque that can be generated by the muscles. It has also been shown that there is a decrease in isokinetic effort at full reach in the sagittal plane to between 28% to 40% of the peak isometric strength at half reach. The arm and wrist orientations result in changes in the mechanical advantage and thus in strength exertion capacity. The highest horizontal isokinetic pull strength of the arm is exerted when in the sagittal plane, while the least strength is in the frontal plane. Dynamic strength is reduced as the speed of exertion is increased. Furthermore, the duration and frequency of exertion leads to a sharp decline in strength (Mital and Kumar 1998a). Other research studies have resulted in the development of numerous human strength models for static and dynamic work scenarios based on anthropometric information from different populations. However, this research will rely primarily on the tables and models presented by Mital and Kumar (1998a,b) for its human strength computations, except where other sources may be more applicable to the specific cases investigated.

Work Energy, Power, and Torque

Work can be defined as any activity involving mental or physical effort expended in order to achieve a purpose or result. This physical effort requires the exertion of muscle force and movement in the direction of the force (Equation 2.3). The work done by a system or body segment is a measure of its useful energetic output. It is the product of the force generated by the segment and the distance over which the force is applied (assuming the force is constant). If, however, the force varies with time, then the work performed is the area under the force-distance graph (Figure 2.15). If the force is applied at a distance (moment or lever arm) from a pivot or fulcrum to produce a turning force, it is termed as torque (Equation 2.4). Power or energy, then, can be defined as the capacity or ability to perform work. Without sufficient energy to expend, there is no capacity and thus the desired work cannot be performed. The amount of work done is determined by the rate at which energy is expended by the respective segment or muscle group. Power can thus be defined more specifically as the rate at which work is performed. This is usually the mean energy expenditure over a time interval (t). The instantaneous power of the segment or muscle can be calculated as the gradient of the work-time graph (Figure 2.16). The magnitude of power delivered to do the work is thus determined by the speed at which work is performed, such that more power is expended to perform work over a short time interval, whereas less power is expended in performing the same work task over a longer time interval. Fatigue results in a reduction in the available maximum energy of the muscles, and this may impact the rate at which power is voluntarily generated/applied to perform the task and, in turn, the amount of work done. This defines the basis for fatigue and productivity relationship.

Work = F_{ACT} x Distance Equation 2.3

Torque = F_{ACT} x Perpendicular Distance Equation 2.4

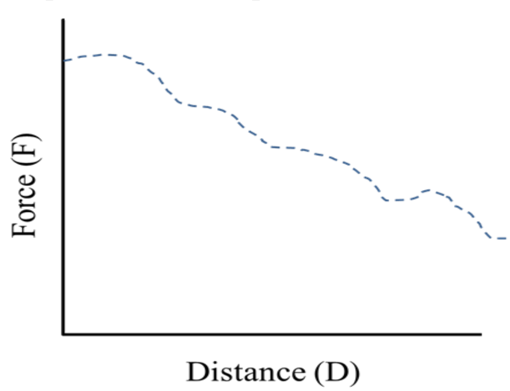


Figure 2.15: Work done by a varying force

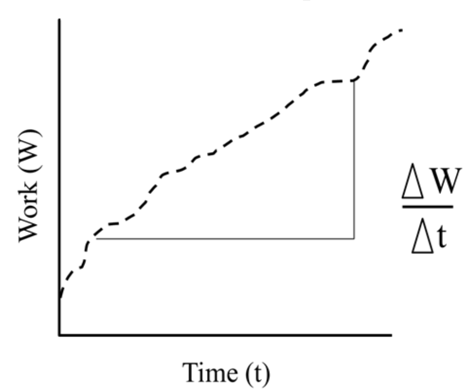


Figure 2.16: Instantaneous Power

2.5.3 Energy and Fatigue

An early physical demand assessment of occupational activities is important in work design, as such information can be incorporated in the design to ensure worker safety and reduce the potential for developing a WRMSD. Activities involving material handling lead to cumulative stress and loading of the musculoskeletal system and may pose different degrees of risk for WRMSDs. This is heightened where there is an insufficient allocation of time for rest and recovery and may result in reduced efficiency and productivity. An industry perspective on fatigue looks particularly at its short- or long-term effects on employee efficiency on the job. The industrialist, therefore, defines fatigue as whatever changes occur as a result of work which result in decreased employee production. Work constraints may lead to execution of work under a variety of postures and reach which determine the magnitude of stress experienced by the muscle and the also the power that can be exerted during task execution. Productivity may be affected by fatiguing muscles as the amount of time to execute a task is increased to compensate for the reduced muscle strength. Rohmert (1973b) defines fatigue as a state characterized by *feeling of tiredness* combined with a *reduction or undesired variation in performance* of the activity. He also notes that *not all functions of the human organism become tired as a result of use.* This shows that while certain areas/muscles may be fatigued, others may not be. The "*theory of differential* fatigue" as presented by Kumar (2001) states that depending on the activity, different joints are differentially loaded, and, depending on the motion to be performed, different muscles operating the joints may also be differentially loaded. This differential loading of muscles may not be proportional to the individual muscle capability, where different muscles may undergo varying amounts of fatigue, and the rate of fatiguing may be different. Liu et al. (2002) have defined fatigue as the rate at which the muscle has reduced its ability to perform activities. This is controlled by the fatigue factor or fatigue effect, (i.e., the rate at which the activated muscle motor units are moved into the fatigued state), and the recovery factor, (rate at which the fatigued muscle motor units are recovered from the fatigued state). Fatigue may be objective (resulting from a decline of muscle force resulting from exertion), or subjective (weariness due to bodily or mental exertion). The definitions suggest that fatigue is a state of reduced physical ability which can be restored through sufficient rest. Different task requirements result in different energy consumption/costs and thus different rates of energy depletion. The rate of energy usage can be correlated to the local muscle fatigue of the muscle exploited over the time interval. The feeling of fatigue indicates an inability of the body to continue or repeat an effort. This signal helps prevent exhaustion and serious muscle damage. Fatigue may originate due to one or a combination of the following factors:

- energy depletion and delivery in the muscle;
- an accumulation of metabolic by-products such as lactate;
- overexertion of muscular contraction mechanisms;
- events in the nervous system.

Fatigue is also affected by one or a combination of the fitness of the individual, intensity/type of effort exerted, muscles involved, and an individual's motivation to accomplish task. Thus fatigue is further categorized either as (1) central fatigue—fatigue perception induced by the brain and central nervous system or (2) muscular fatigue—also referred to as local muscle fatigue. The latter is an inability of the muscles to maintain or generate a specific amount of muscular force over time. The above description shows fatigue as being dependent on the magnitude and duration of effort compared to the muscle strength capability. Thus, the greater the muscular exertion, the shorter the period during which specific strength (power) can be maintained (Kroemer et al. 2010)

Local Muscle Fatigue

Muscle fatigue is the failure of the muscle to maintain a required or expected force or a loss of maximal force-generating capacity during exercise (Encyclopedia of the Neurological Sciences, 2003). Daily work tasks expose the musculoskeleton to varying degrees of stress which may lead to fatigue and injury. Construction operations usually involve repeated exposure to multiple ergonomic risk factors, manual material handling, and awkward postures which may expose the worker to cumulative muscle stress and fatigue in a typical working day. The time it takes to reach the point of fatigue determines the duration within which the worker can maintain a steady state of energy for work. Muscles have been shown to demonstrate cumulative fatigue proportional to the degree or duration of exposure to continuous loading due to work execution. Fatigue results in a reduction in available muscle energy, and this also presents the risk of a reduction in accuracy and thus increased potential for other forms of workplace accidents and errors, leading to rework, reduced efficiency, and injury. It is thus important to understand the relationship between the degree of ergonomic risk exposure and worker productivity and efficiency, as well as the relationship between muscle fatigue and muscle strength, in order to aid in the design of work processes (durations of exposure to muscle stressors) to maintain optimum worker performance. Since muscle strength returns after sufficient rest/recovery and the degree of fatigue is directly proportional to the available muscle strength (% of MVC), work designs which reduce muscle fatigue will improve worker efficiency and productivity while reducing the incidence of WRMSDs. This knowledge is useful for the design of work tools and rest/recovery cycles. Various static and dynamic muscle fatigue models have been developed in the existing research which have successfully presented relationships that will be useful in designing appropriate work recovery interventions based on muscle strength-fatigue relationships (Ma et al. 2009; Dedering et al. 2002; Troiano et al. 2008).

Local muscle fatigue (objective or muscular fatigue) usually occurs at low levels of energy output where loads are applied to a localized group of muscles. Fatigue results in the reduction of MVC and strength of the muscles over time due to the energy expended to do work as well as the work conditions. Thus, after a time interval Δt from the task inception, the worker's strength (S_2) and potential maximum power output (MVC) will be less than at the beginning of the task (S_1). The maximum energy or strength available for use to do work at the current time S_2, then, is a percentage of the muscles MVC at peak strength. The resulting loss of strength can be determined as:

$$\Delta S = S_1 - S_2 \qquad \text{Equation 2.5}$$

Where ΔS is the loss in strength over the time interval Δt, and S_1 and S_2 are the initial and current MVC of the fatiguing muscle.

Endurance is a measure of how much work a muscle can perform. Endurance measures the number of times a specific muscular task can be repeated before the subject needs to rest (point of exhaustion). Fatigue precedes exhaustion, and endurance can either be *relative* or *absolute*. The ***relative endurance*** of a muscle is the number of times the muscle can carry a percentage of its maximum voluntary contraction (such as the number of times to lift 50% of MVC). However, the ***absolute endurance*** is the number of repetitions of a fixed task that can be performed before exhaustion sets in, (such as the number of times one can lift 50kg to the point of exhaustion).

Relative Strength

The terms relative strength, relative force, and endurance time describe relationships commonly used to assess the development of localized muscular fatigue as a consequence of isometric contractions exerted. The relative strength of the muscle is the percentage of MVC after work; the relative force of that muscle is the actual force relative to its maximal voluntary force (Van-Dieen and Oude-Vrielink 1994).

$$F_{REL} = \frac{F_{ACT}}{F_{MVC}}$$ Equation 2.6

Where: F_{REL} = Relative Force of the muscle when compared to MVC, F_{ACT} = Actual force exerted by muscle due to load (to do work), F_{MVC} = Maximum voluntary contraction force.

In most of the literature, it is assumed that there is no muscular fatigue occurring below a relative force of 15 percent (15%). This means that exertion can be sustained indefinitely below this percentage (Rohmert 1959, 1960; Grandjean 1980; Hertzberg 1972; Jorgensen 1970). Others have given different threshold values ranging between 2-20% (Jonsson 1980; Monod and Sherrer 1965; Astrand and Rodahl 1986). This suggests that a little exertion can cumulatively contribute to local muscle fatigue and has resulted in the assessment of endurance time based on the calculation of exerted force relative to MVC (Huijgens 1986). This has led to the development of various relationships. Van-Dieen and Oude-Vrielink (1994) showed through experimental and statistical validation that the concept of isometric contraction, (where muscles generate force without changing its length), was inaccurate and its assumptions that fatigue and endurance time of different muscle groups under different situations are governed by identical relationships was misleading. This was verified by presenting ten (10) factors which influence the relationship between relative force and endurance time (muscle fibre type, blood flow, maximum force, muscle length, muscle temperature, anatomy, anatomical environment of the muscle, lactate concentration in blood, sex, and experimental variations). Van-Dieen and Oude-Vrielink (1994) developed a model equation (Equation 2.7) by analysing data or decomposing the regression coefficients representing the relationships between relative force and endurance time based on Hagberg (1981); Manenica (1986); Rohmert (1959); Rohmert (1960); and Huijgens (1986).

$F_{REL} = a - b \ln(T)$ Equation 2.7

Where: F_{REL} is a % MVC, T is time (min); **a** and **b** are constants the values of which are different for different muscle groups, as shown in Table 2.4.

Table 2.4: Regression coefficients for relationship between relative force and endurance time.

Author	Muscle group	a	b	r
Hagberg 1981				
	Biceps Brachii	61.45	16.99	-0.898
Manenica 1986				
	Biceps Brachii	67.33	22.22	
	Back Muscles	71.23	20.41	
	Body Pull	79.05	23.81	
	Hand Grip	62.44	22.22	
	Body Torque	58.61	23.26	
Rohmert 1959				
	Pronation	53.56	20.28	-0.985
Rohmert 1960				
	Horizontal Pull, 1 arm	53.81	21.19	-0.997
	Horizontal Pull, 1 arm	60.08	19.88	-0.999

Note: r = Pearson's coefficient of correlation.

Equation 2.7 should, however, be used with caution and not unconditionally as several factors indicated above affect the endurance time. An understanding of the relationship between relative force and endurance time is key to fatigue and productivity predictions.

Fatigue is commonly assessed from the perspective of total exhaustion and not on the basis of cumulative stress effect and progressive strength/torque reduction. Also, most applications in the literature focus on static, repetitive work and MVC, and assess work leading to a state of exhaustion. In practice, tasks requiring sustained effort leading to exhaustion are mostly automated; however, the cumulative loss of power generation, or energy depletion, leading to productivity decline is a common phenomenon. Thus the ability to predict the rate of fatigue of muscles will be beneficial for safe and proactive work design and ensure high work productivity. This research attempts to assess the progressive energy loss (fatigue) from non-repetitive construction-related activities and develop quantitative models for assessing local muscle fatigue. Various researchers and NIOSH have focussed on assessing the metabolic energy costs of work. This has resulted in the development of the NIOSH lifting equation for manual handling tasks. However, metabolic cost is outside the scope of this research.

Worker productivity and efficiency

The terms *Work productivity* and *efficiency* are often confused with one another. Work efficiency (E) involves a ratio of the time (T_{ACT}) needed to perform a task relative to a standard or optimum time (T_{OPT}). This is a comparison of what is actually produced or performed with what can be achieved with the same consumption of resources (money, time and labour). Productivity (P), on the other hand, measures the actual work output (W_{ACT}) of a person, machine, factory, or system based on the input cost, either capital, energy, material, personnel, or time, (referred to as C_{IN}), incurred in that time period. Productivity, then, has to do with in converting inputs to useful output.

$$\text{Productivity (P)} = \frac{W_{ACT}}{C_{IN}} \qquad \text{Eqn. 2.8}$$

Based on the above definitions, efficiency is a measure of productivity. Productivity can consequently be assessed based both on material output and time ratio. Many work tasks have predefined production rates (productivity), which are usually predetermined based on the desired quantity needed and the demonstrated peak capacity of the workforce. The worker thus strives to attain this target value. However, although the worker may be operating at the desired productivity level, they may or may not be producing the desired output or operating at peak efficiency. Also, fatigue effects may lead to a reduction in efficiency even though the targeted output is achieved on time. It is thus necessary to determine the required work conditions to facilitate safe and efficient work flow. Work output is assessed by comparing the amount of energy, work, goods, or services produced by a machine, factory, company, or an individual within a measured time period. Efficiency is a comparison of what is actually produced or performed with what can be achieved with the same consumption of resources (money, time or labour). This is an important factor in the determination of productivity.

Over time, continued exposure to risk factors and WRMSDs would result in a decline in worker efficiency and, consequently, productivity. This may be gradual or drastic depending on the degree of injury perceived by the affected worker. Productivity can further be assessed either as resource-based or multi-factorial-based. In resource-based productivity assessment, one of the denominators is the work duration by the labour resource (cycle-time), such that a reduction of the required work duration while maintaining the value-added units will result in increased productivity. Also, from the multi-factorial-based assessment (cost-based) perspective of work productivity, a reduction in the cost of all resources through a reduction in worker compensation, LTCs, work modifications, and hiring costs will result in increased productivity. It can also be inferred, from the U.S. General Accounting Office (GAO) declaration in 1997, that adoption of ergonomic programs can result in up to 80% savings in workers' compensation costs, which are predominantly attributed to WRMSDs. WRMSDs lead to low worker morale and productivity. This may result in work disruptions, lost work time, lost time for investigating the incidence, and lost time and cost for hiring and training a new worker to replace the injured worker (Bernold and AbouRizk 2010). The continued exposure to ergonomic risk factors (stressors) can have a dramatic negative impact on workers. Muscle fatigue, rest and recovery cycles, dynamic and static strength, and environmental stress are all common work-based stressors. An assessment of worker productivity and efficiency with respect to exposure to ergonomic risk factors, task duration, and cycle time for task completion is thus necessary.

2.5.4 Rest and recovery models

Though fatigue and fatigue allowances are important, their determination differs based on the causal factor. A major source of fatigue is the over-exertion of muscle force and frequent high muscle loading during work operations. This often leads to pain and sometimes severe functional disability of muscles and other tissues. An efficient method for assessing physical risk exposure on muscles and fatigue prediction is thus necessary at the work design stage (Ma et al. 2009). The following reviews the existing fatigue allowance models and practice currently applied to work scenarios and the bases of determination of these allowances.

Existing Fatigue Allowance Models

Various allowances are applied to working times in order to compensate for fatigue. These may be in the form of fixed or variable multipliers of normal time, and are set based on work-related factors or environmental factors (Mital et al. 1991). Gaps exist in the literature with regard to the determination of fatigue allowances, such as in cases where the allowance is expressed as a percentage of total shift time. The frequency and duration information required in order to keep within the rest allowance limits are not specified. Usually, a proportionate amount is added to the normal cycle time, or rest is provided when some specific criterion, such as physiological response, is reached. In some cases, fixed multipliers are applied for all jobs regardless of the work, worker, or environment. This leads to inaccurate results since the individual and situational differences are ignored (Karger and Hancock 1982). Some of the standards developed through conventional industrial engineering practice have no relationship with the level of physiological stress involved in moderate strenuous work. Inadequate and excessive fatigue allowances have negating consequences on productivity. While inadequate allowances defeat the purpose of full recovery, an excessive allowance provision is wasteful and both scenarios negatively impact productivity.

Work based fatigue assessments are usually based on the *normal* time (N_T) and *standard* time (S_T). The observed time (O_T) is the time required for an operator to execute a task. When the observed time is adjusted for the pace (rating or speed) of an average worker with adequate experience, it is referred to as normal time (N_T) (Equation 2.9). The standard work time (S_T) is the sum of normal time and rest allowance (R_A) (Equation 2.10). However, if the rest allowance is added as a percentage of the total shift time, then standard work time is determined by Equation 2.11 (Mital et al. 1991).

$$N_T = (\text{Average } O_T) \text{ x Rating} \qquad \text{Equation 2.9}$$

$$S_T = N_T \text{ x } (1 + R_A) \qquad \text{Equation 2.10}$$

$$S_T = \frac{N_T}{1 - R_A} \qquad \text{Equation 2.11}$$

Widely used fatigue allowances are adapted from three different sources (ILO 1979; Cornman 1970; Williams 1973). Although there is no general conclusion as to the best method of assessing fatigue allowances, nor is there an existent clear taxonomy for setting allowances, fatigue causal factors have been seen to be either (i) physiological factors (accounting for force, weight, and gender); (ii) psychological factors (considering strain resulting from visual and mental workload); or (iii) environmental factors (considering humidity, temperature, noise, illumination and air supply). The different sources and contributing factors result in different allowances. For example, Williams (1973) method suggests a 10% minimum fatigue allowance including personal allowance to be added regardless for all tasks; ILO (1979) assumes a fixed 4% allowance to be added for all tasks; and the Cornman (1970) model requires adding all allowances from all factors and subtracting 25% from it. This has resulted in wide differences in allowance ranges (Mital et al. 1991). Based on the physiological fatigue condition, the allowance should consider the magnitude of strain (static muscle fatigue, or increased hear rate); also, the current fatigue percentage and time to achieve full recovery/capacity of the fatigued muscle or return to a resting heart rate should be considered. For environmental fatigue, factors like the extent of core temperature increase and corresponding recovery time are affected by individual differences and differences between the given temperature and atmospheric temperature. The assessment of psychosocial fatigue allowances cannot yet be established, though, as the performance measures have not yet been adequately addressed.

Physiological Fatigue Allowance models

Physiological fatigue allowances assess metabolic expenditure, static isometric strength, and heart rate in order to determine the amount of rest allowance required. These allowances are provided for instantaneous and continuous performance of tasks, based on (i) empirical methods, (ii) static strength, (iii) heart rate, and (iv) metabolic energy expenditure.

Methods based on empirical study

The criteria used in evaluating fatigue in tasks include repetition (frequency), positions (posture), effort (force and static load), and working conditions (organizational factors). Cornman (1970) uses four levels of each criterion by assigning points to each level in determining fatigue allowance. Points assigned at each level based on conditions are converted into allowance percentages. These are then added to previously accumulated percentages from other factors, and 25% is subtracted from the total in order to determine the fatigue allowance as a percentage of total working time. Williams (1973) breaks up physiological factors into energy demands, posture and motions, and restrictive clothing, and recommends fatigue allowance as a percentage of total working time plus a 10% basic minimum allowance for fatigue and personal needs.

Methods based on static strength study (local muscle fatigue)

These methods are based on the maximum voluntary contraction force (F_{MVC}) and maximum holding (endurance) time (T_{MAX}). Thus, muscle fatigue is believed to develop in the exposed muscle group as a function of T_{MAX} and task time (T). T_{MAX} is based on the level of exertion/force with respect to MVC.

Freivads and Goldberg (1988) derived a relationship for maximum holding time (T_{MAX}) and maximum holding force. This relationship is based on Rohmert's conclusion that fatigue only occurs when the applied force is greater than fifteen percent (15%) of MVC (Rohmert 1960).

Also, maximum holding force is normalized by the average of arm, leg, and torso lifting strength (100lbs). Monod and Sherrer (1965) related maximum endurance time at a given level of exertion (P), where P is a proportion of MVC. In this regard, Monod and Sherrer (1965) asserted that an asymptotic point in strength endurance occurs at 14% of MVC. Rohmert (1973b) used the stress-strain approach and proposed that the recovery that can be reached (% of MVC) is independent of force or duration during the work task, but is dependent on the extent of fatigue attained. Here, the stress and strain involved during static and dynamic muscular work are used to determine the degree of fatigue and recovery. Rest allowance thus depends on the extent of muscular exertion (F/F_{MVC}) and the duration of this exertion (T/T_{MAX}). Rohmert here proposed two exponential relationships for determining fatigue allowances for normal muscular work as well as for heavy dynamic muscular work, such as cycling. In Section 2.5.2, it has been shown from various research studies that fatigue develops at a F_{ACT}/F_{MVC} less than 15%.

Methods based on heart rate

Heart rate is influenced both by static and dynamic work. According to Karrasch and Muller (1951) and Muller (1953), the limit of continuous work performance throughout an 8-hour work day is 30 beats/minute above the resting pulse rate. This is the upper limit of work load within which the working pulse does not continue to rise but instead, when work is stopped, returns to resting level after 15 minutes. Since work pulses and maximum heart rates vary throughout the day (average heart rate is 130-140 beats/minute with occasional increases up to 180 beats/minute). Hettinger (1970) proposed a mathematical relationship (Equation 2.12) for determining rest allowance. This allowance should be determined such that the time weighted average working pulse rate does not exceed the resting pulse rate by more than 30 beats/minute. Also, the frequency of extreme increases (170-180 beat/minute) should be less than 5% and they should not last more than 2 minutes.

$$(T_R \text{ X } R_P) + (T_W \text{ X } W_P) / 480 = R_P + 30 \qquad \text{Equation 2.12}$$

Where $T_R + T_W = 480$, T_R = Resting time, T_W = Work time (minutes), R_P = Resting pulse/minute, W_P = Working pulse/minute.

Thus, for a critical case where working pulse rate $W_P = R_P + 30$, for a complete recovery, the resting time for a typical 8-hour work day can be determined by the relationship expressed in Equation 2.13.

$T_R = 480 / T_W \times R_P$ Equation 2.13

Rest allowances should be incorporated several times during the working period.

Methods based on metabolic energy expenditure

These methods are premised on determining the relaxation allowances based on the energy costs of various tasks. Energy cost models are developed (Garg et al. 1978; Ayoub and Woldstad 1999) based on aerobic capacity, gender, anthropometry, work information (such as speed, frequency, and number of cycles) and limits for continuous performance of work per day. Murrell (1965) proposed a relationship between work energy expenditure and standard working rate for the determination of rest allowance (Equation 2.14).

$$R = \frac{B - S}{B - 1.5}$$ Equation 2.14

Where B= Work energy expenditure (kcal/minute), S = Standard working rate (5kcal/minute for male and 4.2kcal/minute for females, 1.5kcal/minute is average energy expenditure at rest).

Various models have been developed for estimating B for different tasks. The main limitation of these models is the assumption of one third (1/3) of the aerobic capacity (about 15kcal/minute for males and 12.5kcal/minute for females) as the limit for continuous performance for an 8-hour work day. Subsequent studies, in fact, have shown aerobic capacity to vary widely based on the task, the work pattern, the muscles used, and the type of person (Mital 1985; Mital and Shell 1984). Based on the total available energy, Mital and Shell (1984) developed a model for the determination of rest allowances as a percentage of work duration (Equation 2.15). This model considers the worker's age, gender, aerobic capacity, number of hours of sleep, leisure time and activities, shift duration, and job energy requirement. For jobs comprising various tasks, the duration and energy requirement for each task are required for this comprehensive model.

$$\text{Rest Allowance}\,(R_A)\,(\%) = \left\{ \left(\frac{\sum J_{ER}}{\text{Adjusted} \sum E_{EAW}} \right) - 1 \right\} \times 100$$ Equation 2.15

Where J_{ER} = Total job energy requirements and E_{EAW} is the adjusted energy available for work.

Physiological fatigue allowance models consider the localized muscle fatigue and recovery, the heart rate rise above the endurance limit and its recovery, or the total energy cost of a task. Several models exist which have not been referenced; however, what has been referenced reflects a general summary of existing models for rest and recovery determination. The models presented here have been proposed by the ergonomics research community for assessing allowances from the physiological fatigue perspective. However, there is no consensus on an acceptable or unified model for determining fatigue allowance. This is due to the limitations demonstrated in these models. The assessment of rest allowances based on psychological and environmental factors is outside the scope of this research.

Limiting Factor Methods

A key to assessing fatigue would be to apply the limiting factor method as a basis for setting the fatigue allowance (Mital et al. 1991). The revised NIOSH lifting equation adopted the limiting factor approach in setting the limits and multipliers for biomechanical, physiological, and psychophysical criteria for safe assessment of lifting tasks, resulting in a conservative model equation (Equation 2.1) to eliminate fatigue and mitigate the risk of WRMSDs (Waters et al. 1993). The limiting factor method provides an assurance of safety based on the most vulnerable muscle. In cases where different muscles or body segments are involved actively in a task's execution, the ergonomic assessment (physical demand analysis, ergonomic risk analysis, fatigue and rest and recover analysis) should consider each body segment or muscle and, using the limiting factor technique, recommend interventions which would assure safety of the limiting muscle or body segment.

Muscle fatigue and Recovery Models

Several research studies have targeted the development of a muscle fatigue and recovery model for work-related physiological fatigue assessments (Wexler et al. 1997; Ding et al. 2000a,b; 2003; Liu et al. 2002; Ma et al. 2009, 2010). A complex physiological-based fatigue model was proposed by Wexler et al. (1997) using Ca^{2+} cross-bridge mechanism, which was verified by stimulation experiments. This model had too many variables (20), with parameters only available for quadriceps, thus necessitating extrapolation to other muscles. This limits the model's application. A force-pH and time relationship in the course of recovery was obtained by Giat et al. (1993) using curve-fitting techniques. Although this model could analyze mathematically the force generation capacity of the muscles, it failed to consider all the influences on fatigue from the muscle forces. For assessing fatigue at the joint level, a half-joint fatigue index model based on mechanical properties of muscle groups was presented by Rodriguez et al. (2003a, b, c). This model applies a posture optimization algorithm to adapt human posture during work dynamically when fatigue appears. However, its half-joint principle as the movement of a joint is activated by several muscles. This model is mostly useful for assessing static postures, as it was the maximum holding time for static postures that was used for developing the model. Rodriguez and Boulic (2008) evaluated the influence of induced passive torques in the stimulation of time-varying human poses. Freund and Takala (2001) accounted for fatigue using force capacity consumption and recovery mechanisms such that the force production capacity varies between zero and its maximum force (F_{MVC}). According to the model developed, the muscle is a kind of reservoir the force production capacity of which reduces with the time the muscle is contracted. At the same time, the reservoir is filled in by the surrounding systems with more capacity. The constant approximations to the fatigue parameters are obtained by fitting the model solution to the Rohmert curve proposed by Chaffin and Andersson (1991). Actually, the various "environmental" factors, such as blood pressure and composition of the muscle (the ratio of slow fibers to fast fibers) have an effect on the fatigue parameters. Liu et al. (2002) developed a dynamic model of muscle activation, fatigue, and recovery in which the fatigue and recovery factors were assessed. The fatigue factor is defined as the rate at which the muscle has reduced its ability to perform activities, which is determined by the rate at which the activated motor units are moved into the fatigued state. The recovery factor is defined as the rate at which the fatigued motor units recover from the fatigued state. The stress-strain behaviour and recovery pattern of the back (disc) with respect to compressive and shear stress should be determined towards the assessment of cumulative loading and recovery and their effect on back pain (WRMSD). Also, the relationship between fatigue and productivity decrease under the non-repetitive work scenario should be determined, a strategy which would be helpful for productivity studies.

Ma et al. (2009; 2010) developed a muscle fatigue and recovery model (Equation 2.16- Equation 2.20) applicable to virtual human modelling programs for evaluation of muscle fatigue based on physiological risk from work. Here, a geometrical and biomechanical model was constructed to calculate the load at each joint using inverse dynamics. This model illustrates that the muscle fatigue index is a function of the maximum voluntary force (F_{MVC}), current maximum voluntary force (F_{CEM}), applied external load (F_{ACT}), and duration of work (Equation 2.16). Furthermore, the current maximum muscle voluntary force (F_{CEM}) is shown as being determined by the initial (previous) F_{CEM}, external applied load, and duration of activity (Equation 2.17).

$$\frac{\partial U(t)}{\partial t} = \frac{MVC}{F_{CEM}(t)} \frac{F_{ACT}(t)}{F_{CEM}(t)}$$ Equation 2.16

$$\frac{\partial F_{CEM}(t)}{\partial t} = -k \frac{F_{CEM}(t)}{MVC} \frac{F_{ACT}(t)}{}$$ Equation 2.17

$$F_{CEM}(t) = MVC\, e^{\int_0^t -k \frac{F_{ACT}(u)}{MVC} du}$$ Equation 2.18

$$F(t) = \int_0^t \frac{F_{ACT}(u)}{MVC} du$$ Equation 2.19

$$\frac{F_{CEM}(t)}{MVC} = e^{-kF(t)} = e^{-kC(t)}$$ Equation 2.20

$$u(t) = \frac{1}{2k} e^{2kF(t)} - \frac{1}{2k} e^{2kF(0)}$$ Equation 2.21

Where: U= muscle fatigue index, $F_{CEM}(t)$ = Muscle capacity at current time (t) (N) , MVC = Maximum voluntary contraction (maximum capacity of muscle) (N), $F_{ACT}(t)$ = External muscle load (Force to be generated by muscle) (N), K = constant value, 1 (min^{-1}). Note, $F_{ACT}(t)/ F_{CEM}(t)$ describes how the generated muscle force is influenced by the current muscle capacity.

This model has been validated with both static and dynamic load cases and is proven to give reliable estimates. It is easily applicable for integration with human modelling applications and has been integrated in a virtual environment. The model has been validated with 24 static endurance time models proposed by El ahrache et al. (2006). The validation results show a high linear relationship using Pearson's correlation (r_{min} =0.85, r_{max} =0.999, r_{mean}= 0.99), and good overall interclass correlation (ICC). It has also been validated with three dynamic models proposed by Ding et al. (2003), and is based on the perception of fatigue (Equation 2.16) and the rate of fatigue (Equation 2.17). This is also based on muscle motor unit force generation capability and different fatiguing and recovery properties resulting from work rate (velocity) and applied force (Ma et al. 2009; 2010).

Muscle recovery from a certain fatigue state was also presented by (Ma et al. 2010) as a function of the previous maximum voluntary strength of the muscle ($F_{CEM\ INI}$), maximum voluntary contraction force F_{MVC}, and recovery time (Equations 2.22 and Equation 2.23).

Muscle Recovery Model

$$\frac{\partial F_{CEM}(t)}{\partial t} = R\left(F_{MVC} - F_{CEM}(t)\right)$$ Equation 2.22

$$F_{CEM}(t) = F_{MVC} + (F_{CEMINI} - F_{MVC})e^{-Rt}$$

$$F_{CEM}(t) = F_{CEM\ INI} + \left(F_{MVC} - F_{CEM\ INI}\right)(1 - e^{-Rt}\ \ )$$

$$t = -\frac{1}{R}\ln\left(\frac{pF_{MVC} - F_{MVC}}{F_{CEM\ INI} - F_{MVC}}\right)$$ Equation 2.23

Where: F_{MVC} -$F_{CEM}(t)$ represents Force/strength loss due to fatigue. $F_{CEM} = F_{MVC} - F_{RES}$. F_{RES} = strength loss due to energy expenditure (reduced capacity or fatigue). p= % MVC, t =recovery time from a certain fatigue level $F_{CEM\ INI}$ to p%, R = recovery ratio, (min^{-1}), R=2.4.

The dynamic fatigue and recovery models offered by Ma et al. (2009; 2010) need further experimental validation in order to be fully accepted; however, the cross validation results with 24 existing and accepted static models and 3 dynamic models have shown the capability to quantitatively assess dynamic muscle fatigue. The theory and quantitative determination process lend themselves to the application of known muscle strength parameters, epidemiological evidence, and anthropometry databases. This model will thus be adapted within this research as a basis for assessing dynamic fatigue resulting from construction tasks.

2.5.5 Physical Demand Analysis

A Physical Demands Analysis (PDA) is a systematic procedure to quantify and evaluate all of the physical and environmental demand components of all essential and non-essential tasks associated with a job. A PDA is the "cornerstone" of the analytical process used to determine compatibility between a worker and a specific job. A PDA breaks up the task in order to examine the physical demand resulting from individual activities, including the use of machines, equipment, tools, and work aids. PDA is usually applied to assess a worker's functional abilities to design back-to-work programs for injured workers in order to avoid causing additional injury.

Steps

1. Determine and verify the job function
    a. Job description and purpose
    b. Identify all essential and non-essential tasks required to execute task
2. Determine Tasks and Duration information
    a. Categorize tasks as essential or non-essential
    b. Quantify duration spent in each task (Total time or % of total time)

    c. Count number of cycles or repetitions of work
3. Quantify task physical demand
    a. Mobility (walking, sitting, standing, stooping, climbing, kneeling)
    b. Manual material handling (lifting, pushing, pulling and carrying)
    c. Reaching (vertical and horizontal work)

See sample PDA in Appendix A.

2.5.6 Anthropometry definitions and model equations

In order to apply a biomechanical assessment, certain anthropometric measures of the human body need to be defined, including gender, height, body weight, age, and lengths of body segments (upper-arm, lower-arm, upper-back, head, neck, and hands). The relative distances between the centre of gravity of each segment and joint axis or other reference landmarks must also be known. Such information has been documented in anatomy and biomechanical research articles. Dempster (1955) studied over a three year period certain anatomical, geometrical, and mechanical features of the limbs of male cadavers in order develop manikins capable of realistic movements and thus useful for understanding body kinematics for aerospace force research of seated aircraft operators. His work has been referenced in this research in determining ranges of feasible motion of joints and geometric information for determination of locations of the centre of gravity of body segments.

Table 2.5 shows relative distances between the centre of mass/gravity of a segment and the joint axis or other landmarks from Table 1 of Dempster (1955). Table 2.6 shows average segment mass ratios (in %) by Roebuck et al. (1975), derived from cadaver studies based on research by Harles (1860), Braune and Fischer (1889), Fischer (1906), Dempster (1955), and Clauser et al. (1969). Table 2.7 shows prediction equations to estimate segment mass (kg) from total body weight (W) as adapted from NASA/Webb (1978).

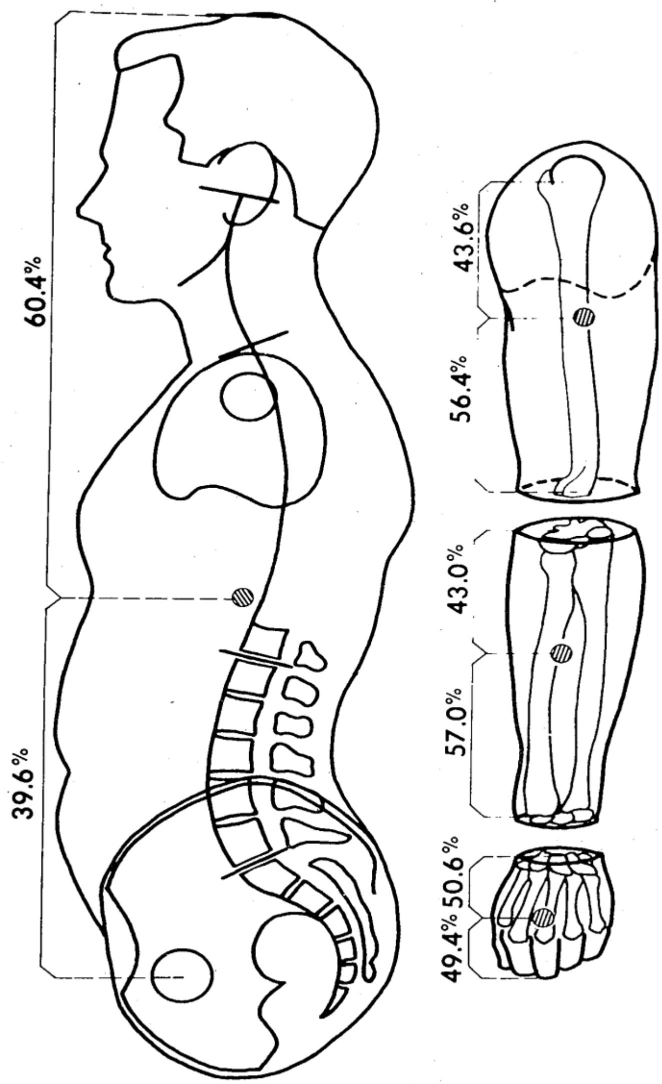


Figure 2.17: Location of segment centre of gravity relative to segment length (Dempster 1955).

Table 2.5: Relative distances between the centre of mass/gravity of a segment and joint axis or other landmarks.

Segment	Reference Landmark	Distance from centre of gravity to refernce dimension (%)
Upper-Arm	Gleno-humeral axis to elbow axis)	43.6% to gleno-humeral axis, 56.4% to elbow axis.
Lower-arm	Elbow axis to wrist axis	43.0% to elbow axis, 57.0% to wrist axis.
Lower-arm plus hand	Elbow axis to ulnar styloid	67.7% to elbow axis, 32.3% to wrist axis.
Upper-Body	Gleno-humeral axis to ulnar styloid	51.2% to gleno-humeral axis and 48.8% to ulnar styloid.
Head and Neck	Vertex to 7th cervical centrum	43.3% to vertex, 56.7% to centrum

Thorax	First Thoracic to 12th Thoracis centrum	62.7% to first thoracic centrum, 37.3% to 12th thoracic centrum.
Head and trunk minus limbs	Vertex to transverse line through hip axis	60.4% to vertex, 39.6% to hip axis.
Head and trunk minus limbs and shoulders	Vertex to transverse line through hip axis	64.3% to vertex, 35.7% to hip axis.
Lower-leg	Knee axis to ankle axis	43.3% to knee axis, 56.7% to ankle axis.
Thigh	Hip axis to knee axis	43.3% to hip axis, 56.7% to knee axis.
Leg plus foot	Knee axis to medial malleolus	43.4% to knee axis, 56.6% to medial malleolus.
Whole lower limb	Hip axis to medial malleolus	43.4% to hip axis, 56.6% to medial malleolus.

From Dempster (1955) Table 1.

Table 2.6: Average segment mass ratios (in %) of total body mass

Segment	Average Mass Ratio (%)
Head	7.8
Trunk	47.2
Total Arm	5.4
Upper-arm	2.9
Lower-arm and hand	2.5
Lower-arm	1.8
Hand	0.8
Total Leg	17.1
Thigh	10.8
Shank and Foot	6.3
Shank	4.6
Foot	1.7
Total Body	**100**

Average mass ratio is a % of total body mass

Total Body mass = Head + trunk + 2(Total leg + Total arm)

Table 2.7: Prediction equations to estimate segment mass (kg) from total body weight (W)

Segment	Empirical Equation	e	r^2
Head	0.0306W + 2.46	0.43	0.626
Head and Neck	0.0534W + 2.33	0.60	0.726
Neck	0.0146W + 0.60	0.21	0.666
Head, neck and Torso	0.5940W - 2.20	2.01	0.949
Neck and Torso	0.5582W - 4.26	1.72	0.959
Total Arm	0.0505W + 0.01	0.35	0.829
Upper-arm	0.0274W - 0.01	0.19	0.826

Lower-arm and hand	0.0233W - 0.01	0.20	0.762
Lower-arm	0.0189W - 0.16	0.15	0.783
Hand	0.0055W + 0.07	0.07	0.605
Total Leg	0.1582W + 0.05	1.02	0.847
Thigh	0.1159W - 1.02	0.71	0.859
Shank and Foot	0.0452W + 0.82	0.41	0.750
Shank	0.0375W + 0.38	0.33	0.763
Foot	0.0069W + 0.47	0.11	0.552

r^2 = Correlation Coefficient e = Standard Error of Estimate

2.6 Work-Related Musculoskeletal Disorders Exposure-Response Relationships

Current and cutting edge research has been conducted and the results analyzed statistically to demonstrate the relationship between exposure to ergonomic risks and evidence of WRMSDs. It has been demonstrated that identified ergonomic risk factors, including awkward work postures, high force and static muscle loading, contact stress, vibration, repetition, hand and whole body vibration, and environmental (heat and cold) factors result in the development of various WRMSDs (Spielholz et al. 2006; Leclerc et al. 1998). Work-related ergonomic risk exposure-response relationships based on the epidemiological studies and published relationships by NIOSH (Bernard 1997) have also demonstrated the ergonomic effects of exposure to multiple risk factors. The relationships identified have been illustrated graphically as an odds ratio of exposure to response (Dekrom et al. 1990; Silverstein et al. 1986, 1987; Armstrong 1993). This has resulted in the recommendations of best practices for work (Entzel et al. 2007).

2.7 Multidisciplinary research focus

Ergonomic assessment of work tasks is a multi-disciplinary area of research which impacts people, profit, and environment. It is further noted that the consequences of work-related MDSs affect the employee, employer, and community. This research encompasses the following core disciplines as shown in Figure 2.18:

- Occupational safety and health
- Health sciences (anatomy, physiology, and epidemiology)
- Structural Engineering (biomechanics, statics and dynamics)

- Construction engineering and management (residential, industrial, infrastructural and commercial)
- Project management and control cost, schedule, absenteeism, planning and design, work improvement)
- Automation and simulation (artificial intelligence, discrete event and continuous simulation)
- Decision support systems (databases, object-oriented modelling)

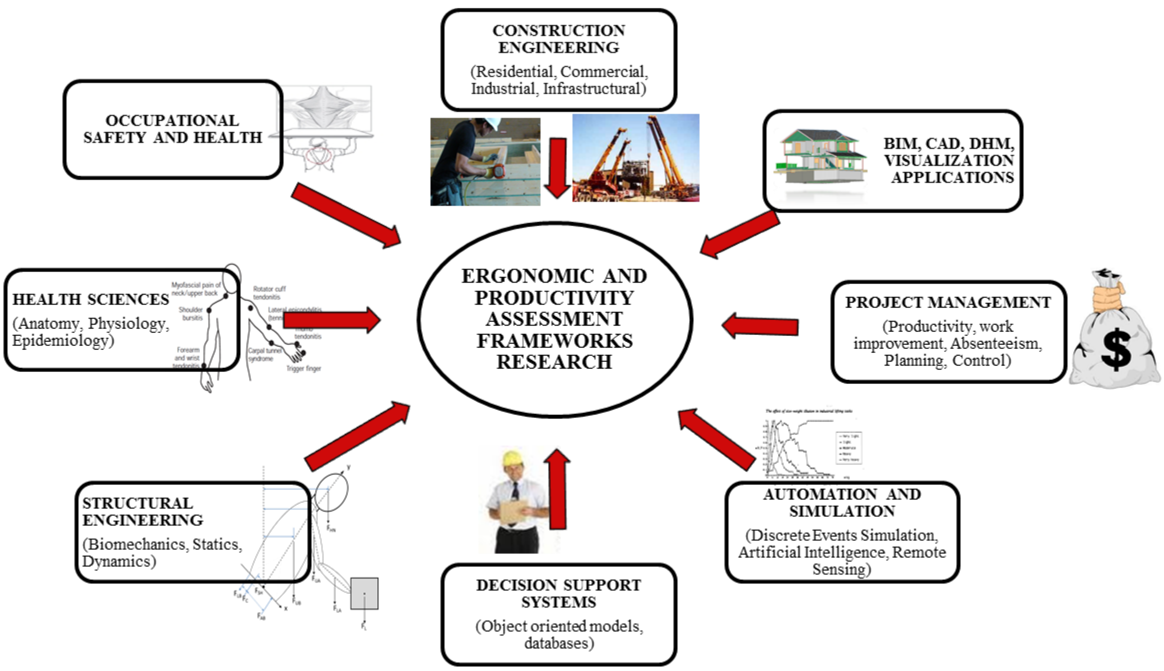


Figure 2.18: Multidisciplinary Research Interaction

A central aim of this research is the improvement of quality of life, making it a complex research requiring thorough studies of diverse techniques and methods with an aim of finding safe work solutions for the construction worker. This area of research is in dire need of participation and encouragement by the construction engineering and management (CEM) community, as the potential impact of this research extends even beyond retirement, affecting the dependents of construction workers in the event of injury/disorder. The effectiveness of this research is contingent upon the knowledge and use of a broad spectrum of complex and expensive equipment for observation, measurement, and modelling of work and a steep learning gradient for understanding and interpreting the results. The transfer of occupational health and safety awareness (specifically ergonomics risk awareness) to CEM students will certainly have a long-term positive impact on the industry.

2.8 Validation Techniques

The quality (and validity) of any data generated or measured is proportional to the following factors: (i) measurement procedure; (ii) data collection and management; (iii) subject-instrument interaction (skill and comfort level); (iv) suitability of equipment/instrument to measure properly; and (v) instrument reliability and validity (based on required reliability, Fagarasanu and Kumar 2002).

Delinger and Leech (2007) have discussed mixed methods validation frameworks, and their discussion has encompassed the concept of inferential validity or consistency. Inferential consistency refers to whether the inferences in a study are consistent, given what is known from prior understandings, past research, and theory. It also focuses on what is appropriate based on the given study design, measurement, and analysis, and assesses whether or not the methodology applied in the study under review was adequate to maximize the amount of information available to answer the selected question and/or purpose as opposed to alternative methodologies (Dellinger and Leech 2007). Messick used the concept of construct validity (Messick 1995), a universal framework for determination of validly of a framework. Here, validity is defined as

> *An overall evaluative judgment of the degree to which empirical evidence and theoretical rationale support the adequacy and appropriateness of interpretations and actions on the basis of test scores and other modes of assessment. (p. 741)*

Validity has either an *evidential* basis or *consequential* basis. The evidential basis of data interpretation is concerned with the availability of systematic evidence linking data to inference, and available evidence justifying the utility and relevance of the data. The consequential basis focuses on the consequences of the use of the data (intended and unintended social implications) and the consequences of data interpretation (implications of interpretation of the values). A cross-validation method can also be applied for assessing the performance of predictive models (Browne 2000). According to Dellinger and Leech (2007), a researcher developing a study must make a number of decisions that have the potential to influence or provide evidence to support construct validation.

The key for proactive ergonomic assessment is the ability to assess the ergonomic risk and impact of cumulative exposure to physical hazards during construction work for extended time periods. In order to achieve this objective, this thesis would focus on developing various physiological ergonomic risk and productivity assessment models and methodologies for residential construction operations. The impact of ergonomic improvements on productivity will be assessed. The framework developed will facilitate both the onsite observation of ergonomic risk and the application of computer methods. Applications of discrete event simulation for assessing ergonomic risk will also be implemented. The validation of the developed frameworks and model equations will be conducted using case studies. These case studies will be developed based on standard or actual anthropometric measures and/or epidemiology and geometric parameters and human anthropometry data from popular ergonomic assessment programs such as Tecnomatix Jack, 3DSSPP, and RULA. NIOSH regulations will also be applied as a safety consideration.

Chapter 3 Research methodology

3.1 Research Framework

This section presents the proposed framework for the ergonomic and productivity assessment of residential construction tasks. Due to the nature of the ergonomics problem and the uniqueness of residential construction tasks and ergonomic assessment needs, existing techniques have been reviewed as presented in Chapter 2; the potential and limitations of the existing methods form the basis for the proposed framework. New models have been developed and adapted to suit the ergonomic assessment requirements of a wide range of typical daily residential construction tasks. The developed models will be compared with existing techniques using case studies in Edmonton, Alberta.

The developed ergonomic assessment framework for residential construction tasks follows five (5) phases: *(i) task selection; (ii) physical demand analysis; (iii) ergonomic analysis; (iv) productivity analysis; and (v) recommendation and redesign.* The proposed framework is presented in Figure 3.1 and the process illustrated in Figure 3.2.

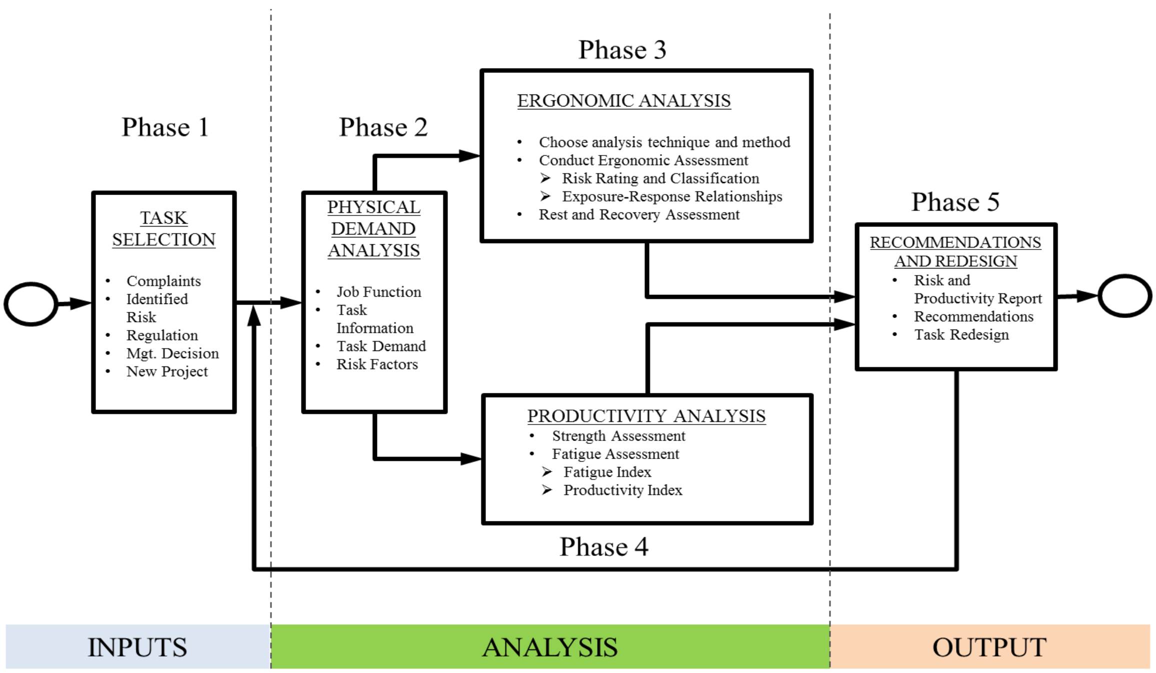


Figure 3.1: Ergonomic assessment Framework

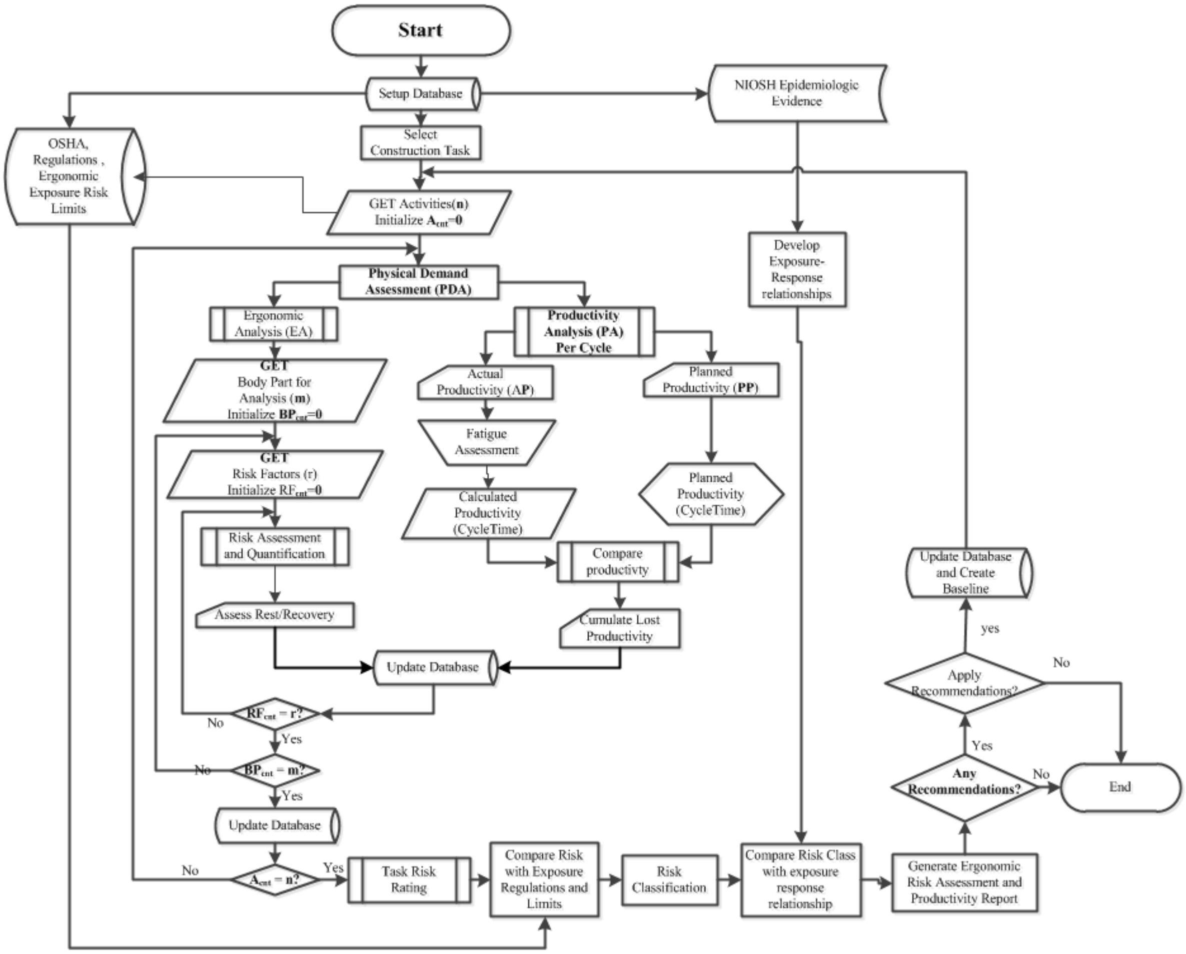


Figure 3.2: Ergonomic analysis implementation process

Phase 1: Task Selection

Prior to execution, the needs and goals of the ergonomic assessment should be reviewed. Time and cost requirements for the selected technique should be understood, including the quality of information to be obtained from the study.

In order to execute an ergonomic assessment, the task to be assessed must first be identified or selected. A task may be selected for assessment as a result of one or a combination of the following: (i) risk complaints from workers; (ii) identified ergonomic risk; (iii) a regulatory requirement or recommendation; (iv) a management initiative; or (v) new project design (PtD).

Phase 2: Physical Demand Analysis (PDA)

The presence of workplace ergonomic risks and the degree/magnitude of risk of work-related musculoskeletal disorders (WRMSDs) due to daily work operations need to be ascertained prior to designing effective control and mitigation strategies. This phase investigates the physical demands of the tasks as they pertain to each body part. It documents information such as task information, cycle times, observed postures, duration of risk exposure, work design and organization, and workers' anthropometry (size and weight proportions of the human body).

A Physical Demand Assessment (PDA), as described in Chapter 2, should be executed in order to identify the task variables and affected body segments. This gives an initial idea of the potential risks and could direct the focus of risk assessment. Refer to appendix A for a PDA sample.

Phase 3: Ergonomic Analysis

Review ergonomic assessment options and select most appropriate technique

As was established in Chapter 2, there are numerous state-of-the-art methods available for ergonomic analysis which can be applied to construction work to assess the risk of WRMSDs. However, the choice of method to be adopted will depend on the objectives of the assessment and the accuracy and precision required. Construction-based ergonomic analysis aims at identification of ergonomic risks with the goal of establishing priorities for reducing or eliminating these risks in order to prevent the onset of WRMSDs.

Residential construction work has substantial task variability and irregular work periods (Forde and Buchholz 2004). There are also several methodological limitations in quantifying mechanical loads resulting from work activities on the musculoskeletal system. There is thus a need to select an assessment method which is sensitive to the variability inherent in the work being assessed and is also quick and easy to learn and use. Common methods which meet these criteria are mostly observation-based techniques such as REBA, RULA, QEC, and OWAS (discussed further below), which are easy to adapt for quick ergonomic assessment. These methods quantify exposure of various body regions (back, neck, shoulder, legs, arms, hands/wrists) to ergonomic risk factors based on comprehensive information on the frequency and duration of particular postures and movements (David 2005; Li and Buckle 1998). However, existing ergonomic analysis models provide only partial analyses of work-related risks. These include, among others: (1) Ovako Work posture Analysis System (OWAS, Karhu et al. 1977); (2) Rapid Entire Body Assessment (REBA, Hignett and McAtamney 2000); and (3) Rapid Upper Limb Assessment (RULA, McAtamney and Corlett 1993). These methods and models are suitable only for ergonomic analysis of awkward work postures. Other models, such as the 3D Static Strength Prediction Program (3DSSPP, University of Michigan 2003), offer both postural and static load analysis functionalities and methods. However, in spite of their wide acceptance, none of the aforementioned models integrate Hand-Arm Vibration (HAV) exposure analysis or the effect of environmental and organizational factors such as cold, work breaks, and rotations/exercise. The ergonomic risk identification tool (CAPP and CPPI Ergonomics Working Group (2000)) offers a step-by-step comprehensive ergonomic analysis methodology and general risk score for each risk factor. However, this tool does not focus on any specific body part and so is not suitable for the purposes of exposure-response hazard correlation. It also fails to provide a methodology for the analysis of crucial construction-related risk factors such as the risk of exposure to HAV exposures. Other ergonomic analysis worksheets and checklists, such as the Great American Insurance Group's (2010) ergonomic task analysis worksheet, mostly provide general activity-based risk classification for each task, such as whether the task falls within the hazard or caution zone based on the duration or frequency of exposure and the presence of single or multiple risk factors.

More specialized ergonomic analysis methods, such as those involving the use of biomedical and biomechanical analysis equipment, have the capability of measuring specific muscle load magnitudes, indicating an increase in risk for the body part observed. The results from the measurements can then be integrated into digital ergonomic analysis tools (Dickerson et al. 2007). This method has a potential for proactive ergonomic hazard analysis, as it offers the option of workplace simulations of magnitude/dose pattern and recovery processes of the isolated body part and, in turn, shows the shape of the exposure-response relationship. However, the endpoints are typically short-term responses that may or may not represent events on the causal pathway to the development of clinical syndromes/disorders (Punnet and Wegman 2004). Among its drawbacks are the associated costs and expertise required to set up and run these types of analyses. Expert/cognitive models and methods such as fuzzy-based systems have also found applications in ergonomic analysis of work-related risks. This provides an avenue for the knowledge and experience of industry experts to be captured and adapted for workplace safety risk evaluations. These systems use subjective information from linguistic terms in defining the universe of discourse where each risk factor's membership is determined. This is subsequently used in determining the degree of risk based on the perceived risk exposure-response relationship. The fuzzy set theory has also been applied to develop a model—Ergonomic Workload Stress Index (EWSI, Chen et al. 1994)—to predict the existence and level of ergonomic workload stress. As mentioned above, the problems associated with this method are the challenge of fitting fuzzy connective and logical operators to human judgmental data in design and evaluation, as well as the issue of the vagueness of natural language. The application of fuzzy technology to ergonomics and for modelling injury risk has thus been limited (Leondes 1999). In another study, an ergonomic assessment framework proposed by Russell and Skibniewski (1990) applies expert judgement to weight tasks based on physical and cognitive demands. Mathematical algorithms are developed and used to assess the potential risk of the assessed task.

Techniques which allow easy, quick, and comprehensive assessment, with sufficient flexibility and reliability for application in analysing multiple tasks and a range of risk factors, will be suitable (David 2005). Methods which fall within this category are the observation-based methods, due to the limited time and resources. As is also by David, supporting this with the development of a decision support model will be very beneficial. Modifications of these methods to ensure more comprehensive and educated analysis and identification of risk factors will thus be advantageous. Based on the results of analysis using simple observational methods, the more sophisticated computer and direct methods may be used if necessary. The adoption of such a methodology allows for the following during analysis:

- Measure of exposure (severity, magnitude of force, postural risk).
- Measure of level, duration and frequency of risk
- Measure of workplace (organizational) and environmental conditions

The results of the analysis should be transferable and applicable for further analysis of workplace risk.

Execute Ergonomic risk assessment

Based on information from the physical demand analysis, as discussed in Chapter 2, the development of ergonomic injury is precipitated by risk exposure. Since different body segments are exposed to different magnitudes of each identified risk factor, a body segment-based ergonomic assessment is recommended for each body part identified in the PDA.

The ergonomic analysis section presents an analysis of the prevailing ergonomic risk factors associated with task execution. This includes analysis of risk factors such as activity repetition, Hand-arm vibration (HAV) or Whole body vibration (WBV) exposure, force and static loading, contact stress, duration of activity/exposure and environmental factors. Mathematical formulas and rating scales are developed within this section which aid in risk analysis, quantification, and the assigning of risk scores. These formulas will be largely adapted from existing research knowledge and ergonomic analysis quantification techniques. Based on the data gathered from the physical demand analysis, the ergonomic hazard is assessed and quantified; the degree of risk is then presented as a rating scale. The ergonomic risk assessment involves a three-part analysis: (i) ergonomic assessment and quantification; (ii) risk rating and classification; and (iii) exposure-response relationship. The methodology presented in Figure 3.3 shows the interaction of the PDA and ergonomic analysis phases within the proposed ErgoCheck model developed for ergonomic risk assessment. Figure 3.4 shows the process of method selection for ergonomic analysis based on data source and assessment.

The methodology presented in Figure 3.4 shows the method selection and analysis process applied to the proposed ergonomic risk assessment methodology (Figure 3.3). This shows how data can be extracted by processing various input sources, such as CAD/Building Information Models (BIM), Digital Human Models (DHM), visualization programs, simulation models, and observed data. Irrespective of the source of work data, information regarding the project (task information, activity durations, and cycle time); information pertaining to the work plan (work rate, floor layout, and recovery cycles); and task risk and physical demand information (risk factors, anthropometry, and physical demand) need to be extracted before ergonomic assessment can be accomplished.

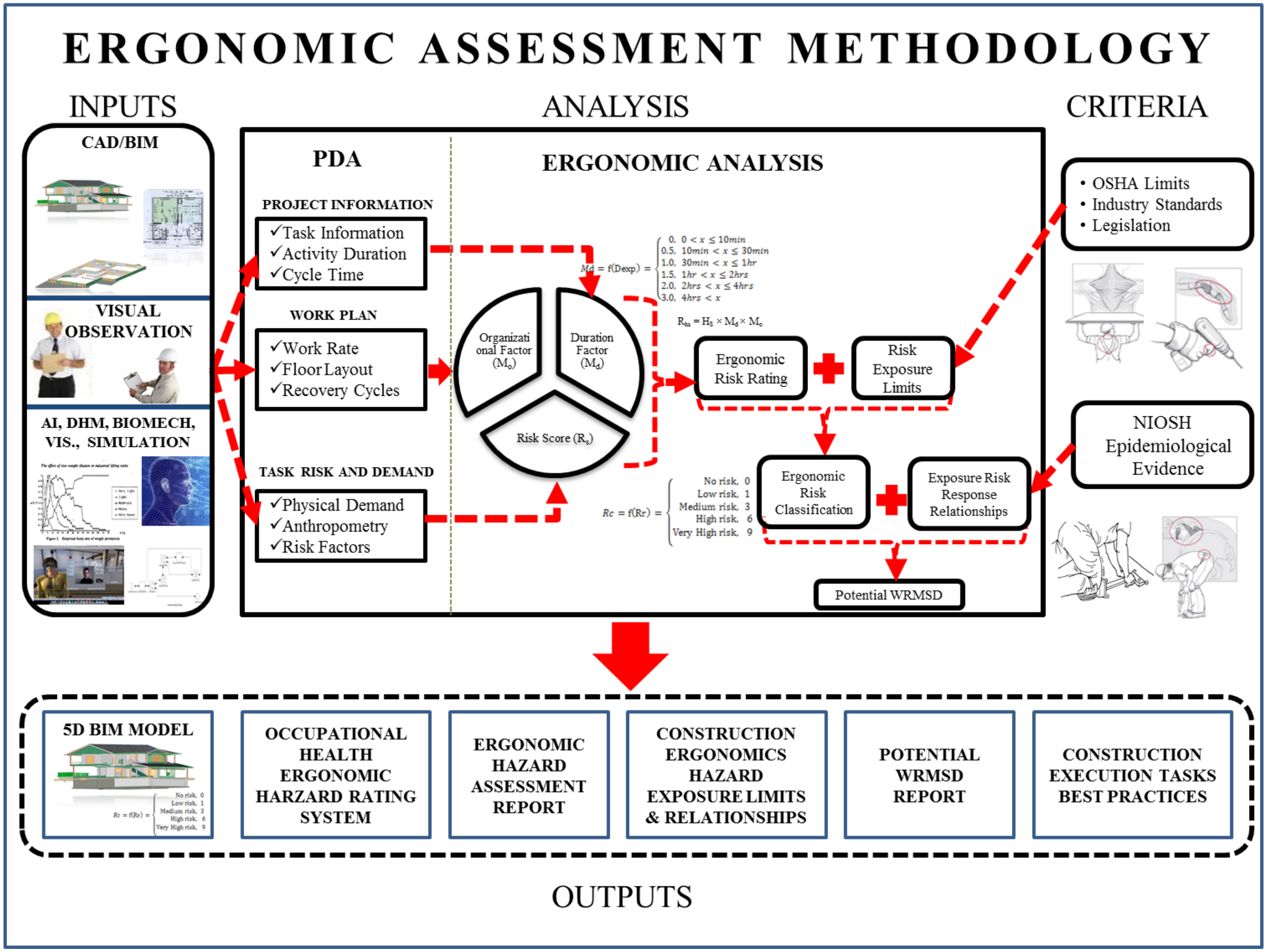


Figure 3.3: Ergonomic Risk Assessment Methodology

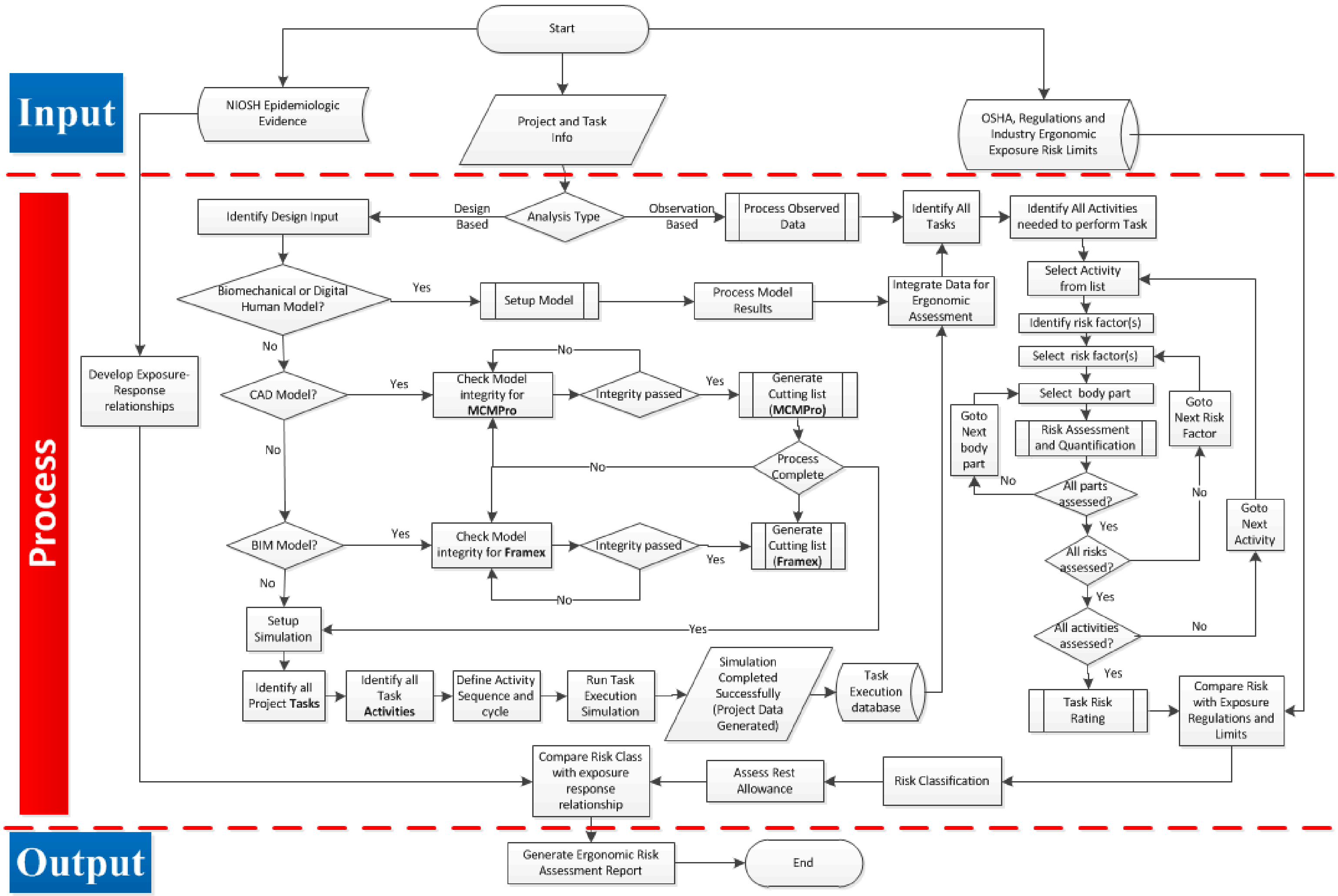


Figure 3.4: Method Selection and Ergonomic Assessment Process

Phase 4: Productivity Analysis

Productivity is assessed based on a comparison of the initial production volume or output of work before and after ergonomic assessment and recommendations. A productivity assessment is conducted simultaneously with the ergonomic hazard assessment. In cases where the current productivity levels have been identified as below the planned output, the effects of pre- and post-ergonomic recommendations are assessed in order to capture the potential onset of fatigue and the relationship between ergonomic hazard and fatigue. This aim here is to validate the thesis hypothesis that *"Careful ergonomic-based design of construction activities will improve construction productivity."*

Various productivity assessment techniques are available and can be utilized in collecting the productivity statistic. These include time studies, rating techniques, digital human models, and simulation applications.

Phase 5: Recommendation and Redesign

As part of the ergonomic risk assessment process, statistics on the degree or classification of risk for each activity and with respect to each identified body part should be collected. The result of the risk assessment should be applied to inform decisions and recommendations aimed at eliminating or mitigating risk and increasing productivity. Such recommendations will target the reduction or control of work-related hazards by implementing appropriate and/or proactive occupational health and safety solutions before the onset of a WRMSDs caused by exertion or overexertion and cumulative trauma of the musculoskeletal system from daily construction activities. The knowledge of potential WRMSDs resulting from cumulative exposure to daily construction-related ergonomic risks will allow for the strategic implementation of control measures.

Controlling exposure to ergonomic hazards is fundamental in occupational safety. National Institute for Occupational Health and Safety (NIOSH) risk control guidelines for ensuring a safer workplace include: (i) elimination; (ii) substitution; (iii) engineering controls; (iv) administrative controls; and (v) Personal Protective Equipment (PPE).

Elimination and Substitution:

These are the most effective controls; however, they are also the costliest to implement on an existing system. This is because major changes in equipment and procedures may be required in order to eliminate or substitute the hazard. This method may be inexpensive, however, if applied at the activity design or development stage. This method is most synonymous with the Prevention through Design technique (PtD).

Administrative controls and personal protective equipment: This refers to procedures and methods, set up by the employer, that significantly reduce exposure to risk factors by altering the way in which work is performed. They are frequently applied to existing processes. Examples include employee rotation, job task enlargement, and adjustment of work pace. They may be relatively inexpensive to establish, but may lead to high costs over the long term. Some of these methods have also been found to be less effective and to require significant effort by the workers.

Engineering Controls: These types of measures control exposure to risk by removing the hazard or providing a protective barrier between the worker and the hazard. These are typically very effective, as they act on the source of the hazard and control employee exposure to it without relying on the employee to take self-protective action or intervention. Examples include changing the handle angle of a tool, using a lighter weight part, using automated equipment, and providing a chair that has adjustability. These measures usually entail a high initial cost when compared to that of administrative controls and PPE. However, in the long term, operating costs are usually lower, and they may lead to cost savings and increased productivity in other areas of the process.

Based on the results of the ergonomic assessments, required modifications, including task, activity, equipment, layout, or process redesign, may be recommended following a review of various applicable alternatives. The Centre for Disease Control (CDC), workplace safety and health compiles a document of simple solutions for construction workers. This provides case studies and recommended approaches towards controlling or eliminating identified and perceived hazards (Albers and Estill 2007). Another document has also been compiled which examines selection of non-powered hand tools (U.S. Department of Health and Human Services 2004). Other valuable NIOSH materials include a workplace hazard evaluation manual (Cohen et al. 1997) and an applications manual for the revised NIOSH lifting equation (Waters et al. 1994).

3.2 Proposed Techniques for ergonomic analysis

This phase presents the development of three (3) proposed ergonomic risk identification, quantification and rating models which are suitable for application to construction work. These include: (i) an observation-based model, *ErgoCheck*; (ii) a dynamic biomechanical model, *ErgoBioMCheck*; and (iii) a discrete event-based ergonomic assessment process application, *ErgoSymulate.* The basis of the proposed fatigue-productivity relationship model is also presented.

3.2.1 Proposed New Observation Based ergonomic analysis model – ErgoCheck

This section presents the step-by-step development of the proposed new ergonomic hazard quantification and rating model (Figure 3.1). The model focuses on:

1) providing an ergonomic risk analysis system capable of assessing residential construction work tasks;
2) identifying ergonomic risk factors related to the construction task being assessed;
3) providing individual risk classification and rating for each body part (neck, shoulder, upper-back, legs, hand/wrist) used in the performance of daily work activities;
4) showing exposure-response relationships between the degree of exposure and potential WRMSDs; and
5) providing an ergonomic analysis methodology which is easy to understand and apply with minimal training.

Methodology

Body part definition: The proposed ergonomic hazard quantification and rating methodology is designed to suit daily construction work-related activities and ensure a comprehensive body part ergonomic analysis. To define the body parts pertinent to this study, the human body is divided into six (6) general segments (movement areas): (i) neck, (ii) arms and shoulder, (iii) hands/wrist, (iv) upper-back, (v) lower-back, and (vi) legs. This allows for observations of risk exposure to these parts, and also paves the way to a correlation of risk exposure to response. The values assigned to the body part postures in Figure 3.5 represent risk scores relative to each work posture.

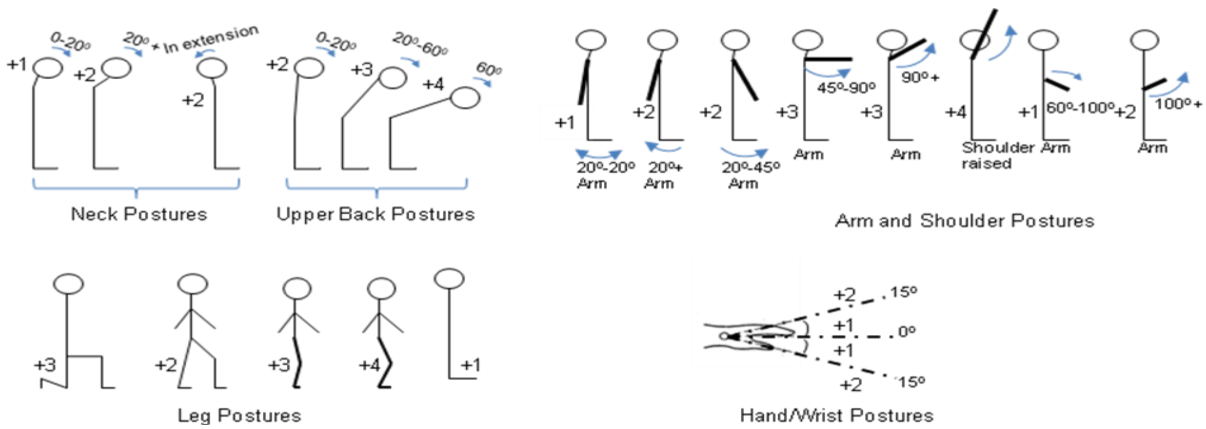


Figure 3.5: Body part analysis postures

Risk Factor Assessment and Rating: Work-related postures are assessed based on identified risks associated with any or all of the following ergonomic risk factors: (i) awkward posture; (ii) repetition; (iii) force and static loading; (iv) contact stress; (v) HAV; and (vi) work environment. Table 3.2 shows the proposed risk analysis and quantification (scoring) methodology, including all applicable variables accounting for ergonomic risks associated with awkward body postures. This is a modification based on the REBA assessment methodology (Hignett and McAtamney 2000), and is applicable for executing a comprehensive work posture hazard exposure analysis.

The proposed analysis method is applied in the following six (6) steps:

Step 1: Postural Analysis: The quantification of postural risk hazard (postural hazard score, R_s) for each body part is based on the maximum risk score obtained from Table 3.2 (after adjustment) and Equation 3.1.

$$R_s = P_{hs} + A_s \qquad \text{Equation 3.1}$$

Where:

P_{hs} = Maximum postural hazard score for body part before adjustment; A_s = Risk score adjustment factor; R_s = Total postural hazard score for body part analyzed

Step 2: Risk Factors Analysis. Table 3.1, Table 3.3 and Table 3.4.Table 3.5 and Table 3.6 show the proposed risk quantification for the remaining five risk factors. This proposed methodology is adapted from the CAPP and CPPI Ergonomics Working Group (2000) analysis methodology. The sum of all risk scores (R_s) for each risk factor is the hazard score (H_s) for that risk factor for the exposed body part. Using Equation 3.2, the resultant hazard score for each risk factor is determined. The daily total HAV exposure is assessed using the Health and Safety Executive (HSE) HAV exposure calculator (HSE 2011), while the risk classification (Table 3.5) is based on WorkSafe Alberta HAV daily exposure limits (WorkSafe Alberta 2011).

Step 3: Organizational Factor (M_o) Analysis: The effects of workplace design, work rate, rest and recovery, and activity rate (organizational risk factor) are assessed based on an abstraction of the CAPP and CPPI Ergonomics Working Group (2000) methodology. This is applied to the other risk factors as an organizational risk exposure multiplier (M_O) using the results of the analysis in and the value in Equation 3.3.

Table 3.1: Repetition Risk Analysis

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

Table 3.2: Postural hazard Analysis

Body Part	Posture	Risk Score	Adjust
Upper Back	Upright	1	Add (+ 1) If twisting or side flexing
	0° - 20° Flexion	2	
	0° - 20° Extension		
	20° - 60° Flexion	3	
	>20° Extension		
	>60° Flexion	4	
Neck	0° - 20° Flexion	1	Add (+ 1) If twisting or side flexing
	>20° Flexion or in Extension	2	
Leg	Both Legs Straight, Walking or sitting	1	Add (+ 1) If knee bent 30° - 60°, Add (+ 2) If bent >60°
	One leg bent slightly (unstable posture)	2	
	Squatting or kneeling	4	No adjustment required
Upper Arm	20° Extension- 20° Flexion	1	Add (+1) if arm is abducted or rotated, Add (-1) if leaning, arm supported, posture is gravity assisted
	>20° Extension	2	
	20° - 45° Flexion		
	45° - 90° Flexion	3	
	>90° Flexion	4	
Lower Arm	60° - 100° Flexion	1	
	<60° Flexion	2	
	>100° Flexion		
Shoulder	Raised	4	
Hand and Wrist	0° - 15° Flexion/Extension	3	Add (+2) if wrist is deviated or twisted
	>15° Flexion/Extension	6	

$H_s = \sum R_s$ (For each body part and risk factor) Equation 3.2

$$Mo = \mathrm{f(x)} = \begin{cases} 0.5, & 0 \le x \le 2 \\ 1, & 2 < x \le 5 \\ 1.5, & 5 < x \end{cases}$$ Equation 3.3

Where: x= organizational hazard score (R_S from Table 3.7).

Step 4: Total daily exposure duration (M_d): Based on the cycle time (CT) of each activity assessed, the duration of exposure to ergonomic hazards (D_{act}) is determined based on Equation 3.4. Meanwhile, the total daily duration of exposure (D_{exp}) of any body part to an ergonomic risk factor is assessed based on Equation 3.5.

$D_{act} = nCT_{act}$ Equation 3.4

$D_{exp} = D_{act} \times P_{ex}$ Equation 3.5

Where: n = number of cycles of activity/day; CT_{act} = Activity cycle time (minutes); D_{act} = total daily time spent on activity; P_{ex} = percent of activity time a specific body part is exposed to risk factor; D_{exp} = total daily exposure duration of risk exposure.

Step 5: The Daily Duration Exposure (M_d): This relates with total daily duration of risk exposure (D_{exp}) based on Equation 3.6:

$$M\text{d} = \text{f(Dexp)} = \begin{cases} 0, & 0 < x \leq 10min \\ 0.5, & 10min < x \leq 30min \\ 1.0, & 30min < x \leq 1hr \\ 1.5, & 1hr < x \leq 2hrs \\ 2.0, & 2hrs < x \leq 4hrs \\ 3.0, & 4hrs < x \end{cases}$$ Equation 3.6

Where: x = D_{exp} (minutes or hours from equation 3.5)

Step 6: Resultant Hazard Score (Hs), Risk Rating (Rr) and Risk Classification(Rc): For ergonomic analysis of each body part, the resultant hazard score for each risk factor identified during the assessment is calculated based on Equation 3.7, and the hazard severity/rating is obtained from Equation 3.8. Equation 3.9 shows the risk levels/classification.

Equation 3.7

$R_{hs} = H_S \times M_d \times M_o$

Where: R_{hs} = Resultant hazard score; H_S = Hazard score (From Equation 3.2); M_d = Duration exposure multiplier; M_o = Organizational exposure multiplier; Note: for the analysis of HAV, M_d is not applicable as it has already been accounted for by the HAV calculator (Let M_d =1).

$$Rr = \text{f(Rhs)} = \begin{cases} 1, & 0 < \text{x} < 6 \\ 3, & 6 \leq \text{x} < 13 \\ 6, & 13 \leq \text{x} < 15 \\ 9, & \text{x} \geq 15 \end{cases}$$ Equation 3.8

Where: x=R_{hs} (resultant hazard score from Equation 3.7)

Table 3.3: Contact Stress Risk Analysis

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

$$Rc = \text{f(Rr)} = \begin{cases} \text{No risk}, & 0 \\ \text{Low risk}, & 1 \\ \text{Medium risk}, & 3 \\ \text{High risk}, & 6 \\ \text{Very High risk}, & 9 \end{cases} \qquad \text{Equation 3.9}$$

Where: R_r = Risk rating and R_c= Risk Class.

Table 3.4: Force/Static Load Risk Analysis

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

Table 3.5: Hand-Arm Vibration Risk Rating

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

Table 3.6: Environmental Factor Risk Analysis

Exposure Variables	Condition	Risk Score
Lighting Conditions	Appropriate lighting. Allows comfortable posture	(+0.5)
	Occassional lighting change results in worker adopting awkward posture	(+1)
	Low or high light level. May cause worker to hunch over or change posture	(+1.5)
Temperatures of objects handled	Comfortably warm objects are handled. Hands not exposed to uncomfortably cold temperatures	(+0.5)
	Moderately warm object/moderately cold temperatures	(+1)
	Object very cold/cold exhaust on hands	(+1.5)
Noise under usual conditions (incl hearing protection if usually worn)	Noise level comfortable and unnoticeable	(+0.5)
	Occassionally uncomfortable and distracting	(+1)
	Very loud, may lead to hearing loss	(+1.5)
Temperature of working conditions (incl effect of seasonal changes)	Comfortable	(+0.5)
	Working temperature occassionally uncomfortable	(+1)
	Working temperature frequently uncomfortable and appropriate PPE not available	(+1.5)

Table 3.7: Organizational Risk Determination

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

Exposure-Response Relationships (ERR)

Although each of the ergonomic analysis options discussed have their merits and provide accurate and acceptable means of determining the potential degree of exertion or overexertion due to work-related activities, methods supported by epidemiology alone provide the relationship necessary for correlating particular exposures with manifestations of WRMSDs over a corresponding exposure time interval and meaningful disease induction period. Furthermore, since multiple risk factors are usually present during exposure, a one-to-one mapping is insufficient to represent the risk exposure-potential disorder relationship. Based on the overall strength of the evidence, the epidemiological relationships between severity of exposure and potential WRMSD have been chosen as the basis for determining the exposure-potential disorder relationship in this study. This method can also be easily adapted for the analysis of construction-related and other work activities. The relationship is based on the epidemiological studies and published relationships by NIOSH (Bernard 1997). The relationships are presented either as an odds ratio (OR), risk ratio (RR) or prevalence odds ratio (POR) (Saunil et al. 2009; Punnett and Wegman 2004). The exposure-response relationship is displayed mathematically as a ratio of comparison between an exposed and an unexposed worker. The POR is easily obtained by use of a logistic regression analysis, available in many statistical packages, and it is thus the most often used terminology (Lee and Chia 1993; Bernard 1997; Osborn and Sofia 1995).

<table>
<tr><th rowspan="2">BODY PART</th><th rowspan="2">MAIN RISK FACTORS</th><th colspan="4">MAIN RISK CLASSIFICATION</th><th rowspan="2">Contributing Risk Factors</th></tr>
<tr><th>LOW</th><th>MEDIUM</th><th>HIGH</th><th>VERY HIGH</th></tr>
<tr><td rowspan="3">SHOULDER</td><td rowspan="2">Repetition</td><td colspan="2">Shoulder Girdle Pain</td><td colspan="2">Shoulder Girdle Pain, Shoulder Tendinitis</td><td>Awkward Posture</td></tr>
<tr><td></td><td></td><td></td><td>Frozen Shoulder, Acromioclavicular syndrome</td><td>Static Load</td></tr>
<tr><td>Awkward Posture</td><td>Cervicobrachial disorder</td><td colspan="3">Cervicobrachial disorder, Shoulder Tendinitis</td><td></td></tr>
<tr><td rowspan="3">ARM</td><td>Repetition</td><td colspan="2">Shoulder Girdle Pain</td><td>Shoulder Girdle Pain, Tension Neck</td><td>Shoulder Girdle Pain, Tension Neck, Shoulder Tendinitis, Acromioclavicular Syndrome, Frozen Shoulder</td><td>Force/ Static shoulder load</td></tr>
<tr><td>Awkward Posture</td><td></td><td colspan="2">Shoulder Pain (w/o Rep or Static load)</td><td>Shoulder Pain, Shoulder Tendinitis, Frozen Shoulder</td><td>Repetition, Static Shoulder load</td></tr>
<tr><td>Force</td><td colspan="4">Shoulder Girdle Pain</td><td>Repetition</td></tr>
<tr><td rowspan="5">HAND AND WRIST</td><td>Repetition</td><td colspan="2">CTS</td><td colspan="2">CTS, Hand/Wrist Tendinitis</td><td>Cold, Force</td></tr>
<tr><td>Awkward Posture</td><td colspan="2"></td><td></td><td>Hand/Wrist Tendinitis</td><td></td></tr>
<tr><td>Force</td><td></td><td></td><td></td><td>Hand/Wrist Tendinitis</td><td>High Repetition</td></tr>
<tr><td rowspan="2">HAV</td><td></td><td></td><td colspan="2">CTS</td><td></td></tr>
<tr><td></td><td></td><td>CTS</td><td>CTS, Vibration White Finger</td><td>Cold</td></tr>
<tr><td rowspan="2">NECK</td><td>Repetition</td><td></td><td></td><td colspan="2">Tension Neck</td><td></td></tr>
<tr><td>Awkward Posture</td><td></td><td></td><td colspan="2">Tension Neck</td><td></td></tr>
</table>

Figure 3.6: WRMSD Body Part Exposure - Response relationship

(Data from NIOSH Epidemiological evidence (Bernard, B. P., July, 1997)

The WRMSDs body part exposure-response relationship matrix represented in Figure 3.6 has been derived from the epidemiologic evidence gathered and presented by NIOSH (Bernard 1997). This evidence shows the relationship between ergonomic risk hazard and WRMSDs for each exposed body part. The exposure-response relationships adapted for this study are those which satisfy the following four research criteria: (1) the investigator was blinded to case and/or exposure status (with regard to worker job status); (2) the risk indicator had to be presented either as an OR, a POR—ratio of risk of a particular outcome or disease if a certain factor or exposure is present, Prevalence risk ratio (PRR)—ratio of the risk among those exposed to that among those non-exposed), Incidence ratio (IR)—comparison of incidence rates in the exposed and unexposed study populations to provide an estimate of the relative strength of association, or RR—ratio of the probability of the event occurring in the exposed group versus a non-exposed group of exposed workers to unexposed workers and with a confidence interval of up to 95%; (3) a minimum study participation rate >/=70% of the affected or selected population; and (4) results that are all based on physical examinations of musculoskeletal disorders (MSDs).

3.2.2 A Cumulative Dynamic Biomechanical model of low-back compressive and shear stress for residential construction applications (ErgoBioMCheck)

Regardless of the level of automation integrated into construction occupations, many activities still involve human intervention. Activities involving material handling expose the worker to stress due to overexertion (strains and sprains) and exertion (cumulative stress) risks. This may result in the onset of WRMSDs and loss of productivity. The effect of insufficient rest and recovery may exacerbate the risk. Work constraints such as reach may increase the amount of stress experienced by the muscles and tendons due to the given postures adopted, which may accelerate local muscle fatigue. An early physical demand assessment of occupational activities is thus important in work design and improvement, as such information can be incorporated into task design to reduce exposure to risk, thereby improving safety. This section presents the development of a mathematical model to quantitatively assess the dynamic low back compressive and shear stress developed during residential construction tasks.

Muscle Forces and Biomechanical Applications

Biomechanics allows basic concepts of static and dynamic equilibrium to be applied to different parts of the human musculoskeletal system using free-body diagrams to estimate the muscle forces generated across the joints and tissues. The estimation/assessment of static and dynamic muscle forces and power exerted or required for executing various construction tasks is necessary for reducing the risk of WRMSDs from cumulative exertion and overexertion. This is because, while performing work, muscles generate and subject other tissues to significant stresses.

A biomechanical assessment of forces and loads simplifies the actual physiologic, anatomic, and anthropometric characteristics of humans in order to accommodate techniques derived for mechanics. This leads to research insight and conclusions into the behaviour of these systems which would otherwise be impossible. It also introduces limitations regarding the reliability, validity, and completeness of anthropometrical procedures. With biomechanics, torques (forces) developed by muscles about body joints can be calculated. This is useful in determining the strain on bones, muscles, and tissues generated by loads on the body in various positions. Furthermore, body segment dimensions, volumes, and mass properties can be calculated from anthropometric data. Kinematics, it should be noted, is the motion of points, bodies, and systems of bodies with respect to a reference frame or with respect to each other, yet without consideration of the forces causing the motion. Kinematic chain models of linked body segments make possible the prediction of total body capability (such as lifting) considering of body segment capabilities.

Daily activities involving back flexion subject the spine to compressive, shear forces and bending moment, and may lead to low back disorders (Jensen 1980; van-Dieen et al. 1999). In flexed postures, the lumbar region is subjected to higher compressive forces than in an upright posture (van-Dieen et al. 1999; Kingma et al. 2010; Kahrizi et al. 2007). The main extensor of the back, the erector spinae muscle group (Leskinen et al. 1983; Merryweather et al. 2009), is made up of three (3) muscle groups—the *spinalis*, *longisimus* and *iliocostalis*, each having different lever arms with respect to the L5-S1 interface. The erector spinae muscles work with the abdominal muscles to help stabilize the torso.

According to Hutton et al. (1979), the total compressive force acting on the lumbosacral joint (L5-S1) is the sum of the forces in the extensor muscles and the components of the upper trunk weight and load lifted.

$$F_{C(L5\text{-}S1)} = \sum(F_{EXT} + F_{UB} + F_{L} + F_{UA} + F_{LA} + F_{HN}) \qquad \text{Equation 3.10}$$

Where F_{EXT} is the lower-back extensor muscle force and F_L, F_{UB}, F_{UA}, F_{LA}, F_{HN} are the components of force due to the load, upper-back, upper-arm, lower-arm, and head and neck, respectively.

In research by Legg (1981), Hemborg et al. (1985) and Chaffin (1969), it has been discussed that intra-abdominal pressure (IAP) reduces spinal stress, (i.e., it serves to unload or unwind the spine), during lifting due to its synergistic action with the contraction of the extensor muscles (Marrass and Mirka 1996; Daggfeldt and Thorstensson 2003). This is due to the fact that IAP increases when executing tasks which load the spine, such as lifting, and also helps to increase spine stiffness and stability (Hodges et al. 2001; Hodges et al. 2005). It can thus be inferred that an increase in abdominal pressure force (which acts in antagonism with the extensor muscle force) would help reduce potential risk of injury from lifting tasks. This emphasizes the importance of physical fitness (tightened abdominal muscles) with respect to lifting activities. Based on this, Equation 3.10 can be modified to Equation 3.11 by introducing IAP force. Figure 3.7 shows the system geometry and forces on a human body during a symmetrical lift (sagittal plane). Figure 3.8 shows a model of a worker lifting a load. Biomechanical assessment will be focused on dynamic symmetrical stoop lifting in the sagittal plane, assuming no torsion or axial rotation is present. Strength assessments will thus be limited to isokinetic strength capacity for lifting under these conditions. Figure 3.9 shows the forces, acceleration, and torque notations adopted.

Compressive and shear loads are created on the lower-back during a lift as a result of the accelerative forces acting on the upper body weight of the worker and the weight of the external load (Merryweather and Bloswick 2008). Posture is stabilized and gravitational force is counteracted primarily by the erector spinae muscles in the back and the antagonist abdominal muscles (McCook et al. 2007; Davarani et al. 2007; Mokhtarzadeh et al. 2012). Back compressive force (BCF) and shear force lead to low back pain (LBP) and injury at the L5-S1 intervertebral disc (Merryweather et al. 2009; El-Rich 2005; El-Rich et al. 2004). Figure 3.7 shows the system geometry of forces acting on the segments during manual handling activities. Here, the abdominal muscle force (F_{AB}), compression force (F_{COMP}) and shear force (F_{SH}) are represented. The NIOSH work practice guide for manual lifting states that “biomechanical compression forces on the L5-S1 disc are not tolerable over 650kg (1430lb) in most workers, but that a 350kg (770lb) force is acceptable for most young healthy males (Merryweather et al. 2009).

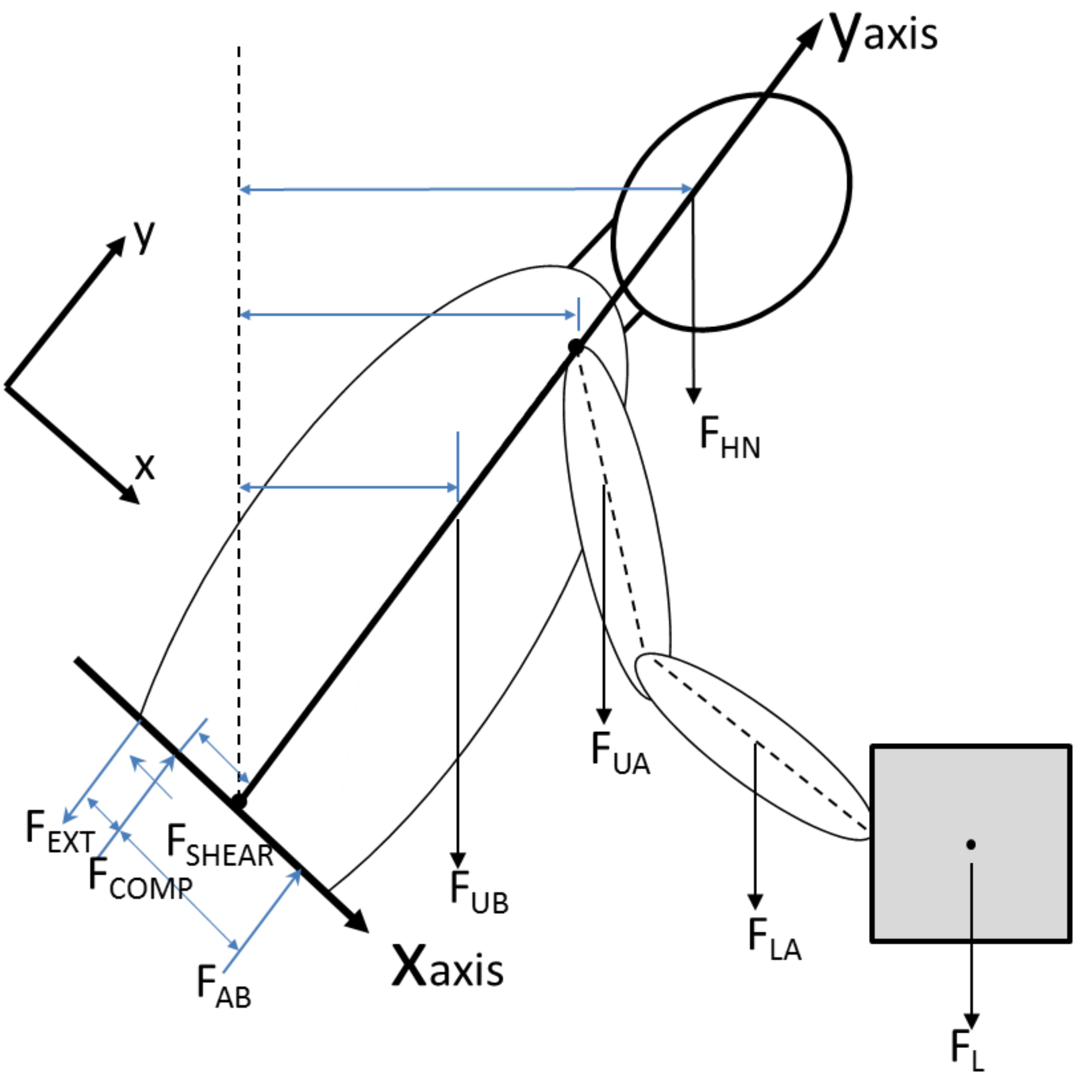


Figure 3.7: System Geometry and Forces

[Modified Courtesy S.M. Klisch, Cal Poly, San Luis Obispo, CA]. The Y-axis is along the back, X-axis is perpendicular to the back.

A biomechanical assessment of forces and torques on the body during motion and work activities can be carried out by applying the free-body diagram with human kinematic chain model (Figure 3.10). This covers all forces acting on the body segments while executing work tasks and thus encompasses the physical demand on body segments to be quantified. Based on the results and limitations as shown in the reviewed literature, it is generally agreed upon that greater accuracy in predicting the magnitude of BCF to which the spine is exposed during work activities can be attained by considering the additional forces generated during acceleration of the body segment's centre of mass as well as the external load (Bazrgari et al. 2007; Bazrgari et al. 2009).

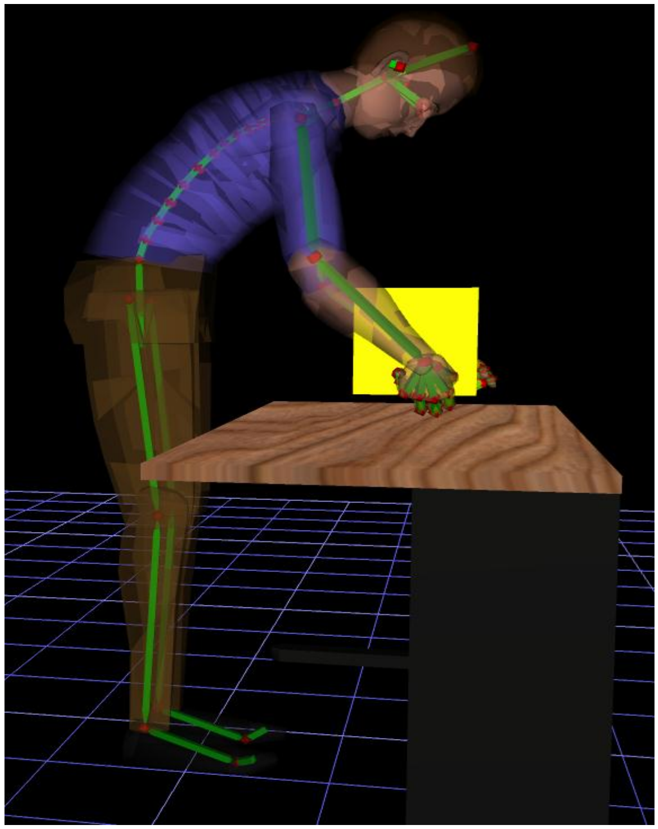


Figure 3.8: Human model Siemens Tecnomatix Jack

$F_{C(L5\text{-}S1)} = \sum(F_{EXT} + F_{UB} + F_{L} + F_{UA} + F_{LA} + F_{HN}) - F_{AB}$ Eqn. 3.11

Where F_{AB} is the abdominal muscle force and F_{EXT} is the low back extensor muscle force exerted acting at the L5/S1 disc over a perpendicular distance D_{EXT}.

The total compressive forces at the L5-S1 disc can be assessed using the force-torque analysis (reactive force components and torque) around the shoulder due to an external load and transferring the forces and torques at the shoulder to the L5-S1 region, (determining the sum of forces in the extensor muscles) (Hutton et al. 1979; Leskinen et al. 1983; Merryweather and Bloswick 2008). Merryweather and Bloswick (2008) carried out a similar study of dynamic BCF to see the changes with respect to different lifting speeds. Figure 3.10 shows a free-body diagram representation of forces acting during lifting activities.

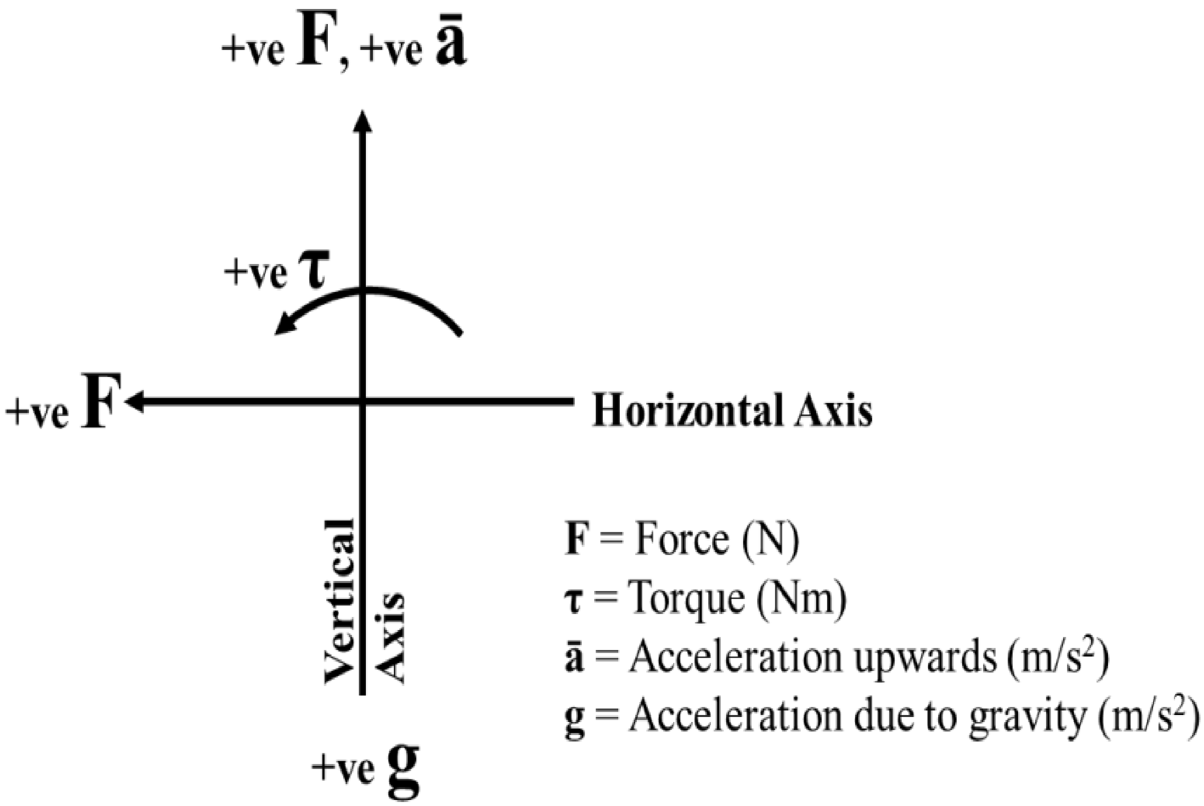


Figure 3.9: Forces, acceleration, and torque notations

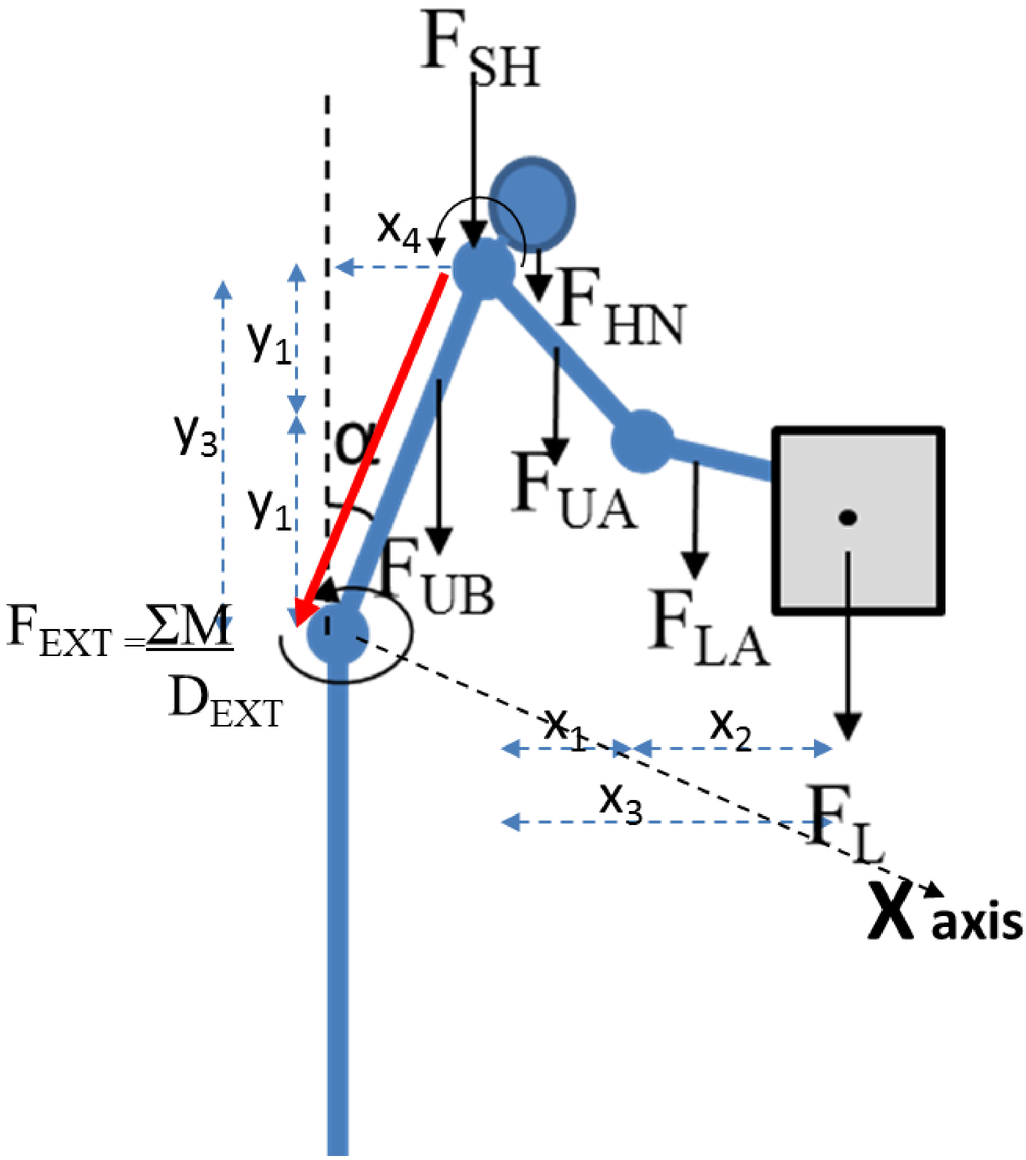


Figure 3.10: Free-body diagram showing forces, moments and horizontal and vertical distances

Reactive Forces and Torques at body articulations

Accelerating masses result in reactive (inertia) forces and torques, according to Newton's second law of motion. The masses offer resistance to any changes in their angular velocity, referred to as the body's moment of inertia. Horizontal and vertical components of linear acceleration acting at the centre of gravity of the body segment can be used to determine these inertia forces. Reactive forces and torques can be estimated using a free-body diagram approach. Equilibrium conditions also have to be assessed for the forces and torques.

$\Sigma F_{i(X)} = 0$ Equation 3.12

$\Sigma F_{i(Y)} = 0$ Equation 3.13

$\Sigma \tau_{i(o)} = 0$ Equation 3.14

Where: $\Sigma F_{i(X)}$ and $\Sigma F_{i(Y)}$ are the algebraic sums of horizontal and vertical forces and $\Sigma\tau_0$ is the algebraic sum of moments and torques about each joint.

Reactive forces and torque at the shoulder

Based on the research by Hutton et al. (1979), Leskinen et al. (1983), and Merryweather and Bloswick (2008) (shown in Figure 3.10), the reactive forces across the shoulder are determined as the sum of the horizontal ($F_{SH(x)}$) and vertical ($F_{SH(y)}$) force components. These forces represent the external load and the acceleration of the centre of mass of the upper and lower-arms.

1) <u>Horizontal reactive force at the shoulder due to segments and load</u>

$F_{SH(x)} = F_{L(x)} + F_{UA(x)} + F_{LA(x)}$ Equation 3.14a

$F_{LA(x)} = M_{LA}$ X $a_{LA(x)}$ Equation 3.14b

$F_{UA(x)} = M_{UA}$ X $a_{UA(x)}$ Equation 3.14c

$F_{L(x)} = M_L$ X $a_{L(x)}$ Equation 3.14d

Where M_{LA} and M_{UA} are, respectively, the masses of lower and upper-arm (acting at each segment's centre of mass) and $a_{LA(x)}$, $a_{UA(x)}$ and $a_{L(x)}$ are the horizontal acceleration (m/s^2) components of the lower and upper-arm segments' centres of mass and load.

Therefore, the horizontal force at the shoulder due to the external load and the arm weight (Equation 3.14a) can be re-written as Equation 3.14e.

$F_{SH(x)} = M_{L(x)}$ X $a_{L(x)} + M_{UA(x)}$ X $a_{UA(x)} + M_{LA(x)}$ X $a_{LA(x)}$ Equation 3.14e

Horizontal acceleration (load + segment) $a_{(x)} = \Delta x/\Delta t^2 = \Delta V_{(x)}/\Delta t$ Equation 3.14f

Where Δx = Horizontal displacement of the load or segment; $\Delta V_{(x)}$ = Horizontal velocity of the load or segment; $\Delta t = t_2 - t_1$= Time interval (duration) of motion(s)

2) <u>Vertical reactive forces at the shoulder due to segments and load</u>

Similar to the horizontal reaction forces, vertical forces at the shoulder $F_{SH}(y)$, due to an external load can be expressed as:

$F_{SH(y)} = F_{L(y)} + F_{UA(y)} + F_{LA(y)}$ Equation 3.15a

Where $F_{L(y)}$ is vertical reaction force due to the external load, and $F_{UA(y)}$, $F_{LA(y)}$ are the vertical reaction forces due to the weight of the upper and lower-arms, respectively.

According to Leskinen et al. (1983) and Merryweather and Bloswick (2008), for dynamic lifting, the accelerative forces are accounted for. Therefore,

$F_{L(y)} = M_{L(y)} (a_g + a_{L(y)})$ Equation 3.15b

$F_{LA(y)} = M_{LA(y)} (a_g + a_{LA(y)})$ Equation 3.15c

$F_{UA(y)} = M_{UA(y)} (a_g + a_{UA(y)})$ Equation 3.15d

Where: a_g is acceleration due to gravity, $a_{L(y)}$, $a_{LA(y)}$, $a_{UA(y)}$ are the vertical accelerative component of the load, lower and upper-arms, respectively.

3) <u>Total force at shoulder due to segments and load</u>

Therefore, Eqn. 3.15a becomes

$F_{SH(y)} = M_{L(y)} (a_g + a_{L(y)}) + M_{UA(y)} (a_g + a_{UA(y)}) + M_{LA(y)} (a_g + a_{LA(y)})$ Equation 3.15e

For equilibrium, total forces at the shoulder (F_{SH}) will be;

$F_{SH} = F_{SH(x)} + F_{SH(y)}$ Equation 3.16a

$F_{SH} = M_{L(x)} a_{L(x)} + M_{UA(x)} a_{UA(x)} + M_{LA(x)} a_{LA(x)} + M_{L(y)} (a_g + a_{L(y)}) +$ Equation 3.16b

$M_{UA(y)} (a_g + a_{UA(y)}) + M_{LA(y)} (a_g + a_{LA(y)})$

Note, the force F_{SH} generated by the shoulder muscles must equal the sum of these three (3) force components and gravity in order for the system to be in equilibrium.

4) <u>Torque around the shoulder</u>

The total torque around the shoulder (τ_{SH}) is the summation of the horizontal and vertical moments at the shoulder due to the load and arm weight and vertical acceleration during lifting, plus the torque due to angular displacement of the arm about the shoulder axis during lifting (Leskinen et al. 1983; Merryweather and Bloswick 2008). The total torque, then, includes the inertia and angular velocity of the shoulder. According to Newton's second law of motion, for a two-dimensional rotational motion, the relationship between torque and angular acceleration can be described by the following equation:

$\tau = I\alpha$ Equation 3.17a

$\tau_{SH} = M_{L(y)} (a_g + a_{L(y)})x_3 + M_{L(x)} a_{L(x)}y_3 + M_{UA(y)} (a_g + a_{UA(y)})x'_1 +$

$M_{UA(x)}\, a_{UA(x)} y'_1 + M_{LA(y)}(a_g + a_{LA(y)})x'_2 + M_{LA(x)}\, a_{LA(x)} y'_2 + I_1\, \alpha_1$ Equation 3.17b

Where: x'_1, x'_2, y'_1, y'_2 are the displacement (horizontal and vertical) from the centre of mass of the upper and lower-arms to the shoulder. x_3 and y_3 are the horizontal and vertical displacement of the load to the shoulder joint. I_1 = mass moment of inertia of the upper limbs around the shoulder. This is the force required to change the angular motion of the arm about the shoulder (axis of rotation). $x_3 = x_1 + x_2$, $y_3 = y_1 + y_2$ and $I = mr^2$. $M_{UA(y)}$, $M_{UA(x)}$, $M_{LA(y)}$ and $M_{LA}(x)$ are the horizontal and vertical components of the upper- and lower-arm segments. r = lever arm. α = angular acceleration—the rate of change of the angular velocity of the arm at the shoulder joint during the activity.

Reactive forces and torque at the lower-back

At the lower-back, the erector spinae muscles have to generate sufficient force and torque to equal the forces and torques at the shoulder, resulting in compression and shear on the L5-S1 disc. To satisfy equilibrium, the forces and moment generated by the erector spinae and abdominal muscles must be equal to the forces and moments at the shoulder due to the external load and arms (F_{SH}), and the forces and moments due to the weight and acceleration of the upper-back (F_{UB}) and head and neck (F_{HN}). Similar to the forces and moments at the shoulder, the forces and moments at the lower-back can be estimated by the following equations:

$F_{LB(x)} = F_{SH(x)} + M_{UB} \text{ X } a_{UB(x)} + M_{HN} \text{ X } a_{HN(x)}$ Equation 3.18a

$F_{LB(y)} = F_{SH(y)} + M_{UB}\, (a_g + a_{UB(y)}) + M_{HN}(a_g + a_{HN(y)})$ Equation 3.18b

$\tau_{LB} = \tau_{SH} + F_{SH(y)}x_4 + F_{SH(x)}y_4 + M_{UB}(a_g + a_{UB(y)})x'_4 + M_{UB}a_{UB(x)}y'_4 + M_{HN}(a_g + a_{HN(y)})x'_5 + M_{HN}a_{HN(x)}y'_5$ Equation 3.19a

Where: I= mass moment of inertia for the upper body (head, neck, trunk) around the L5-S1 disc.

x_4, y_4 = horizontal and vertical displacement from the shoulder (pivot) to the L5-S1 disc.

x'_4, y'_4 = horizontal and vertical displacement from the centre of gravity of the upper-back to the shoulder. x_5, y_5 = horizontal and vertical displacement from the head and neck to the shoulder.

x'_5, y'_5 = horizontal and vertical displacement from the centre of gravity of the head and neck to the shoulder.

The back extensor (erector spinae) muscle group creates a torque equal and opposite to τ_{LB} at the L5-L1. This torque (moment) acts upon the spine with a lever arm (D_{EXT}) (Merryweather et al. 2009) which is the perpendicular distance from the L5-S1 interface to the erector spinae muscle group, and it represents the effective moment arm of the extensor muscles. As such, the extensor muscles must exert a force equal to F_{EXT}. The perpendicular distance D_{EXT} has been estimated to be between 5cm and 6.86cm from the L5/S1 interface (Leskinen et al. 1983; Merryweather and Bloswick 2008; Merryweather et al. 2009; Greenland et al. 2011).

$$\tau_{LB} = F_{EXT} \times D_{EXT}$$ Equation 3.19b

$$F_{EXT} = \tau_{LB} / D_{EXT}$$ Equation 3.19c

Estimation of abdominal pressure forces and torques

El-bassoussi (1974) and Garg and Herrin (1979) applied the work of Chaffin (1969), which was based on the data by Morris et al. (1961), to estimate the contribution of IAP on the lumbar spine. The IAP helps to unwind compression at the L5/S1 disc (Marrass and Mirka 1996; Daggfeldt and Thorstensson 2003), where the IAP developed is related to the magnitude of trunk torque supported. This increases as a function of trunk velocity (Marras and Mirka 1996). Equation 3.20 shows the proposed model relationship between abdominal pressure and hip torque, and the angle between trunk and thighs (El-bassoussi 1974; Garg and Herrin 1979).

$$P_{AB} = 10^{-4}[43 - 0.36\,(180-\Phi)]\,[\tau_{LB}^{1.8}]$$ Equation. 3.20

Where: Φ = angle between the trunk and thigh in degrees (trunk flexion angle); τ_{LB} = torque at the lower-back (NM); P_{AB} = estimated abdominal pressure (mmHg) with maximum of 150mmHg

Four conditions were assumed by El-Bassoussi (1974) in order to estimate the force created by abdominal pressure. These conditions, based on statistical measurements from cadaver studies, are similar to those proposed by Chaffin (1969), Fisher (1967) and Morris et al. (1961):

1. The abdominal pressure acts on a diaphragm area of 465cm^2.
2. The abdominal muscles do not cause a longitudinal pull in lifting. Bartelink (1957) and El-Quaaid et al. (2009) show that the rectus abdominis is not active during lifting.
3. The abdominal vertical force component line of action is parallel to the line of action of the normal compressive force on the lower lumbar spine. (El-Quaaid et al. 2009).
4. Troup (1965) showed that the distances (lever arm) from the spine that abdominal forces act are not constant. Morris et al. (1961) and Fisher (1967) showed that at a 0° trunk flexion, the lever arms decrease approximately 53% from a 60° flexion, and increases by 17% at a 90°

trunk flexion. Chaffin (1969) assumed that the moment arms vary as the sine of the hip angle, the erect posture being 6.7cm at diaphragm level and the 90^o hip angle being 14.9cm at the diaphragm level.

Garg and Herrin (1979) estimate the abdominal force as a product of the abdominal pressure (P_{AB}) and diaphragm area. Here the diaphragm area (D_A) is assumed to be equal to $465cm^2$.

$F_{AB} = P_{AB}$ X $D_A = P_{AB}$ X 465 Equation. 3.21

The moment arm (D_D) of the abdominal force (F_{AB}) is calculated using the model equation 3.22.

$D_D = 12.7$ [Sin (0.5 X Φ) + 0.47] Equation. 3.22

(Note: 1mmHg = $133.28N/m^2$; $1N/m^2 = 1.020*10^{-5}kg/cm^2$; 1mmHg =$1.3595*10^{-3}kg/cm^2$)

Total compression at the Lower-back (L5-S1)

$F_{COMP} = F_{EXT} – F_{AB} + F_{LB(y)}$ Cos α + $F_{LB(x)}$ Sin α Equation. 3.23

$F_{SHEAR} = F_{LB(y)}$ Sin α + $F_{LB(x)}$ Cos α Equation. 3.24

Where: F_{COMP} and F_{SHEAR} are the vertical compressive force and horizontal shear forces on the disc, respectively, while α = angle of trunk from vertical (Figure 3.10)

Quantitative Equations for Biomechanical Dynamic Assessment of Back Compressive Forces for different Postures and Loading Scenarios

1) Model Basis and assumptions

General posture- and loading-based scenarios have been considered in the attempt to develop a methodology for quick assessment of potential dynamic back compression forces arising from construction work requirements. These assessments have been limited only to the symmetrical postures in the sagittal plane, with no axial rotation and lateral bending. Although this introduces potential limitations to the assessment, it provides simplicity as well as a safe base for assessment of ergonomic risks. It is assumed that lifting is performed with both hands, load is of a uniform shape, and the weight of load is uniformly distributed to both hands. The following four (4) scenarios have been assessed in order to cover the generality of loading conditions:

Scenario1: stationary, neutral/upright (free standing) posture with hands by the side (no load)

Scenario2: stationary and upright posture with load in front (load position may be different depending on task)

Scenario 3: walking (upright posture)

Condition (i) without load (hands by side)

Condition (ii) with load in front

Scenario 4: Lifting and lowering of load from an initial height A to a final height B

Condition (i) bend, reach to touch load or bend up to upright posture

Condition (ii) lift or lower load from initial height (A) to place at final position (B)

Case 1: load initial position (A) is below shoulder height and load final position (B) is below or at shoulder height ($A, B \leq S_H$) or vice versa (Lifting or lowering of load)

Case 2: load initial position (A) is below shoulder height and load final position (B) is above shoulder height ($A \leq S_H$) ($B \geq S_H$) or vice versa (lifting or lowering load)

Case 3: load initial position (A) is at or above shoulder height and load final position (B) is above shoulder height ($A, B \geq S_H$)

The four (4) scenarios can be divided into two (2) categories: static scenarios and dynamic scenarios. Scenarios 1, 2 and 3 are grouped as static since it is assumed that there will be no horizontal or vertical displacement of the body segments or load during the activity. These scenarios are thus static, thereby eliminating the acceleration components of Equation 3.10 – Equation 3.24. Scenario 4, however, is considered to be dynamic since it involves various cases which may result in horizontal and vertical displacement and acceleration of the load and each segment's centre of mass. Derivations for linear and angular acceleration components for the reactive torques and moments are required for these cases in order to quantify compressive and shearing forces and torques on the L5-S1 disc.

2) GROUP 1: Static Scenarios

Scenario1: Stationary, neutral/upright posture with hands by the side

The framework for assessment of reaction forces and torques is made based on an upright free posture (Figure 3.11).

Assumptions for Scenario 1:

- Posture is upright/neutral, and the back angle $\alpha=0^o$ (compare Figure 3.11 with Figure 3.12) to the vertical plane.
- Hands are by the side, thus $x_1= x_2= x_3= x_4= x_5= 0$.

- There is no movement at this instant, thus the horizontal (x) and vertical (y) acceleration of the upper-arm, lower-arm, head and neck, and upper-back centres of gravity are zero. ($a_{UA(x)} = a_{UA(y)} = a_{LA(x)} = a_{LA(y)} = a_{HN(x)} = a_{HN(y)} = a_{UB(x)} = a_{UB(y)} = 0$).
- There is no load in hand, thus the mass of load (M_L) and load acceleration are zero ($a_L = 0$).
- Horizontal reaction forces at the shoulder (F_{SH}) and lower-back (F_{LB}) are zero.

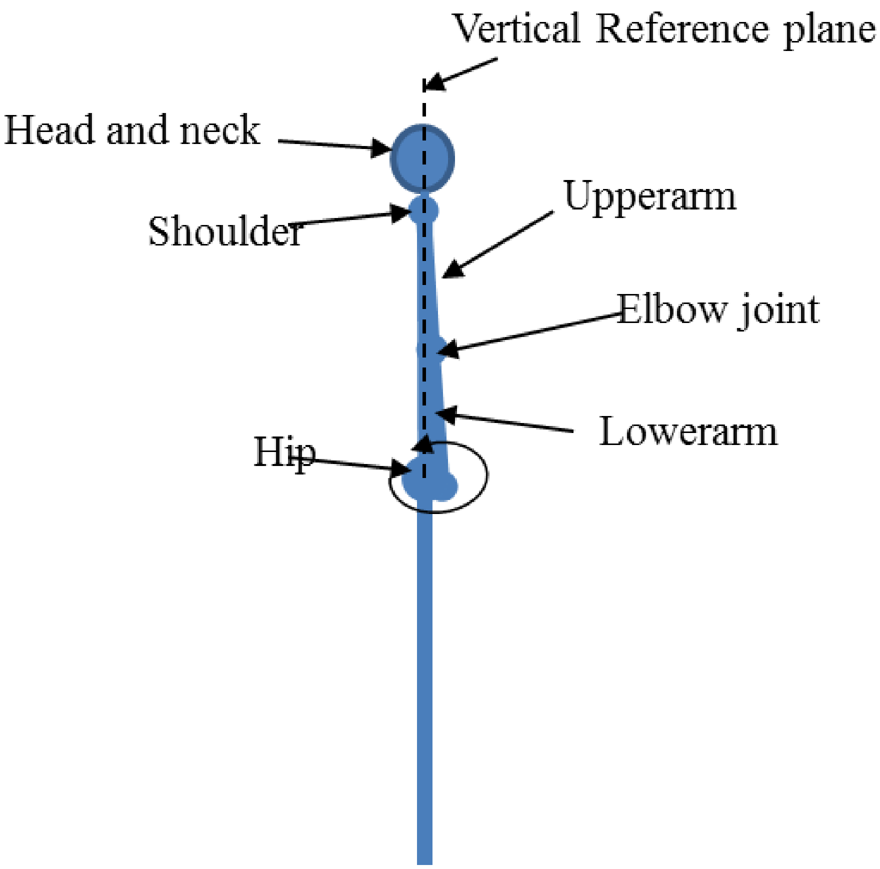


Figure 3.11: Free-body diagram showing an upright free posture with hands by the side

Based on the assumptions above for this scenario, at the shoulder, Equations 3.14e, 3.15e and 3.17b become:

$F_{SH(x)} = M_{L(x)} X\ a_{L(x)} + M_{UA(x)} X\ a_{UA(x)} + M_{LA(x)} X\ a_{LA(x)} = 0$ Equation 3.25a

$F_{SH(y)} = M_{UA}(a_g) + M_{LA}(a_g)$ Equation 3.25b

($F_{SH(y)}$ is due to the weight of the upper and lower-arms, a_g is gravitational acceleration = 9.81m/s^2).

$\tau_{SH} = 0$ Equation 3.25c

The resultant zero torque in Equation 3.25c shows that there is no motion at shoulder.

Also, at the lower-back, Equations 3.18a, 3.18b, 3.19a and 3.19c become:

$F_{LB(x)} = 0$ Equation 3.26a

$F_{LB(y)} = F_{SH(y)} + M_{UB} (a_g) + M_{HN}(a_g)$ Equation 3.26b

$\tau_{LB} = 0$ Equation 3.26c

There is no extension at the lower-back, thus no torque by extensor muscles.

Since $F_{EXT} = 0$, $F_{LB(x)} = 0$, $\alpha = 0^o$ the total compression and shear forces at the lower-back (L5-S1 disc) in Equations 3.23 and 3.24 become:

$F_{COMP} = F_{LB(y)} - F_{AB}$ Equation 3.26d

$(\text{Cos}\ \alpha = \text{Cos}\ 0 = 1)$

$F_{COMP} = M_{UA}(a_g) + M_{LA}(a_g) + M_{HN}(a_g) + M_{UB} (a_g) - F_{AB}$ Equation 3.26e

$F_{COMP} = 9.81(M_{UA} + M_{LA} + M_{HN} + M_{UB}) - F_{AB}$ Equation 3.26f

$F_{SHEAR} = 0$ Equation 3.26g

From Equation 3.26f, the vertical compressive force on the L5-S1 disc at the lower-back when standing upright and stationary with hands by the side is equal to the weight of the upper-back, hands, and head and neck. Also, there are no shear forces acting on the disc in this condition (Equation 3.26g).

Scenario2: Stationary and upright posture with load in front

$F_{SH(x)} = M_{L(x)} \text{ X } a_{L(x)} + M_{UA(x)} \text{ X } a_{UA(x)} + M_{LA(x)} \text{ X } a_{LA(x)} = 0$ Equation 3.27a

$F_{SH(y)} = M_{L(y)}(a_g) + M_{UA(y)}(a_g) + M_{LA(y)}(a_g)$ Equation 3.27b

$F_{SH} = F_{SH(y)} = M_{L(y)}(a_g) + M_{UA(y)}(a_g) + M_{LA(y)}(a_g)$ Equation 3.27c

$\tau_{SH} = M_{L(y)} (a_g)x_3 + M_{UA(y)} (a_g)x'_1 + M_{LA(y)}(a_g)x'_2 + I_1 \alpha_1$ Equation 3.27d

$F_{LB(x)} = 0$ Equation 3.27e

$F_{LB(y)} = (M_{L(y)} + M_{UA(y)} + M_{LA(y)}) a_g + M_{UB(y)} (a_g) + M_{HN(y)}(a_g)$ Equation 3.27f

$\tau_{LB} = (M_{L(y)}x_3 + M_{UA(y)}x'_1 + M_{LA(y)}x'_2 + M_{UB(y)}x'_4 + M_{HN(y)}x'_5)a_g$ Equation 3.27g

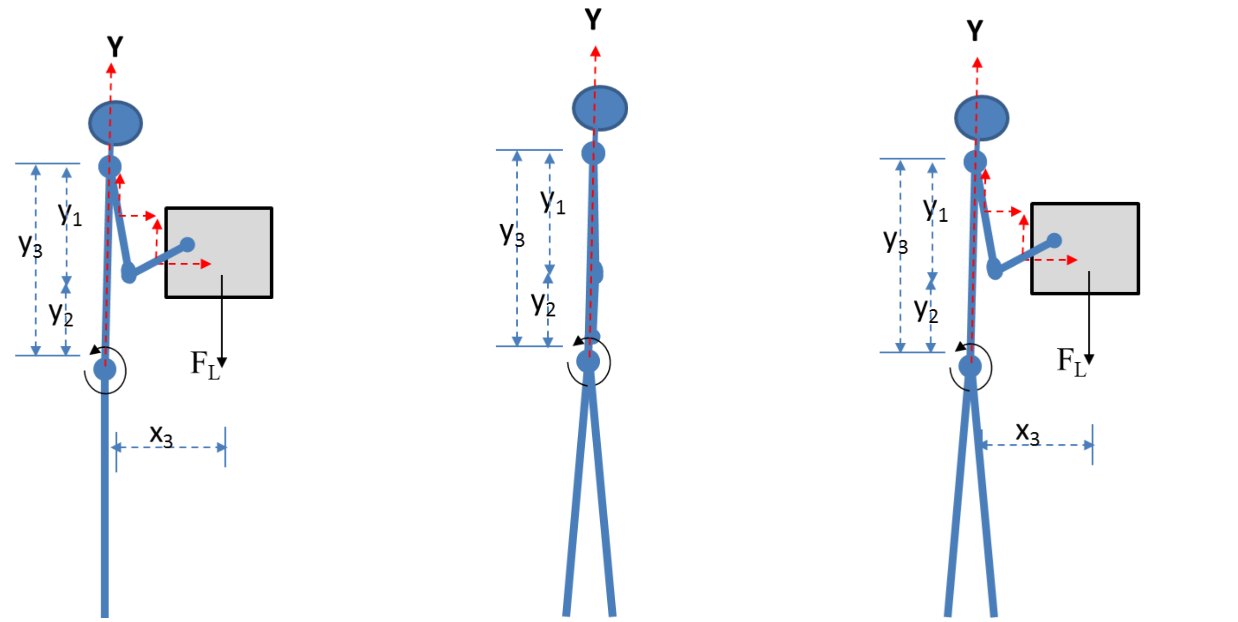
From Equation 3.27g, it can be seen that the torque at the lower-back (L5-S1 region) is caused by the load and the weight of the upper extremity and head and neck.

$$F_{EXT} = \frac{9.81}{D_{EXT}}(M_{L(y)}x_3 + M_{UA(y)}x'_1 + M_{LA(y)}x'_2 + M_{UB(y)}x'_4 + M_{HN(y)}x'_5)$$ Equation 3.28a

$F_{COMP} = F_{EXT} + F_{LB(y)} \cos \alpha - F_{AB}$ Equation 3.28b

$F_{COMP} = 9.81/D_{EXT}(M_L x_3 + M_{UA} x'_1 + M_{LA} x'_2 + M_{UB(y)} x'_4 + M_{HN} x'_5) +$
$9.81(M_L + M_{UA} + M_{LA} + M_{UB} + M_{HN}) - F_A$ Equation 3.28c

$F_{SHEAR} = 0$ Equation 3.28d



(a) Standing with load (b) Walking without load (c) Walking with load

Figure 3.12: Neutral standing and walking postures with and without load

Scenario 3: Walking (Upright posture)

Condition (i) - Without load (hands by side): This scenario assesses the total compressive and shear stresses on the L5-S1 disc during a walking activity, assuming no load is carried and the hands are hanging or swinging freely by the side (Figure 3.12b). For Scenario 1, Equations (3.25a – 3.26g) apply to determining the reactive forces and torques. In order to determine the total compressive and shear stresses forces or bending moments at the L5-S1 disc, the result from an applicable Equation (3.25a – 3.26g) is multiplied by the time interval (Δt = duration of walking activity).

$F_{COMP} = F_{COMP(Eqn\ 3.26f)} \times \Delta t$ Equation 3.29a

$F_{SHEAR} = F_{SHEAR(Eqn\ 3.26g)}\ X\ \Delta t$ Equation 3.29b

Condition (ii) with load in front: This scenario assesses the total compressive and shear stresses on the L5-S1 disc during a walking activity, assuming a load is carried with the hands in front of the body (Figure 3.12c). For Scenario 2, Equations (3.27a – 3.29b) apply to determining the reactive forces and torques. In order to determine the total reactive forces or torques at the L5-S1 disc, the result from an applicable Equation (3.27a – 3.29b) is multiplied by the time interval (Δt = duration of walking with load activity).

$F_{COMP} = F_{COMP(Eqn\ 3.28c)}\ X\ \Delta t$ Equation 3.30a

$F_{SHEAR} = F_{SHEAR(Eqn\ 3.28d)}\ X\ \Delta t$ Equation 3.30b

3) GROUP 2: Dynamic Scenarios

Equations 3.10 - 3.26e apply fully to these scenarios. Only the displacement and acceleration components need to be derived, as these are determined on a case-by-case basis.

Figure 3.13 shows notations and points of action of the centre of mass of the load, as well as of each body segment. The reference angles and the plane of reference to be used in the assessment of the acceleration components are as shown in the figure. The following model equations have been derived for the horizontal and vertical displacements of the upper-arm, lower-arm, upper-back, and head and neck segments.

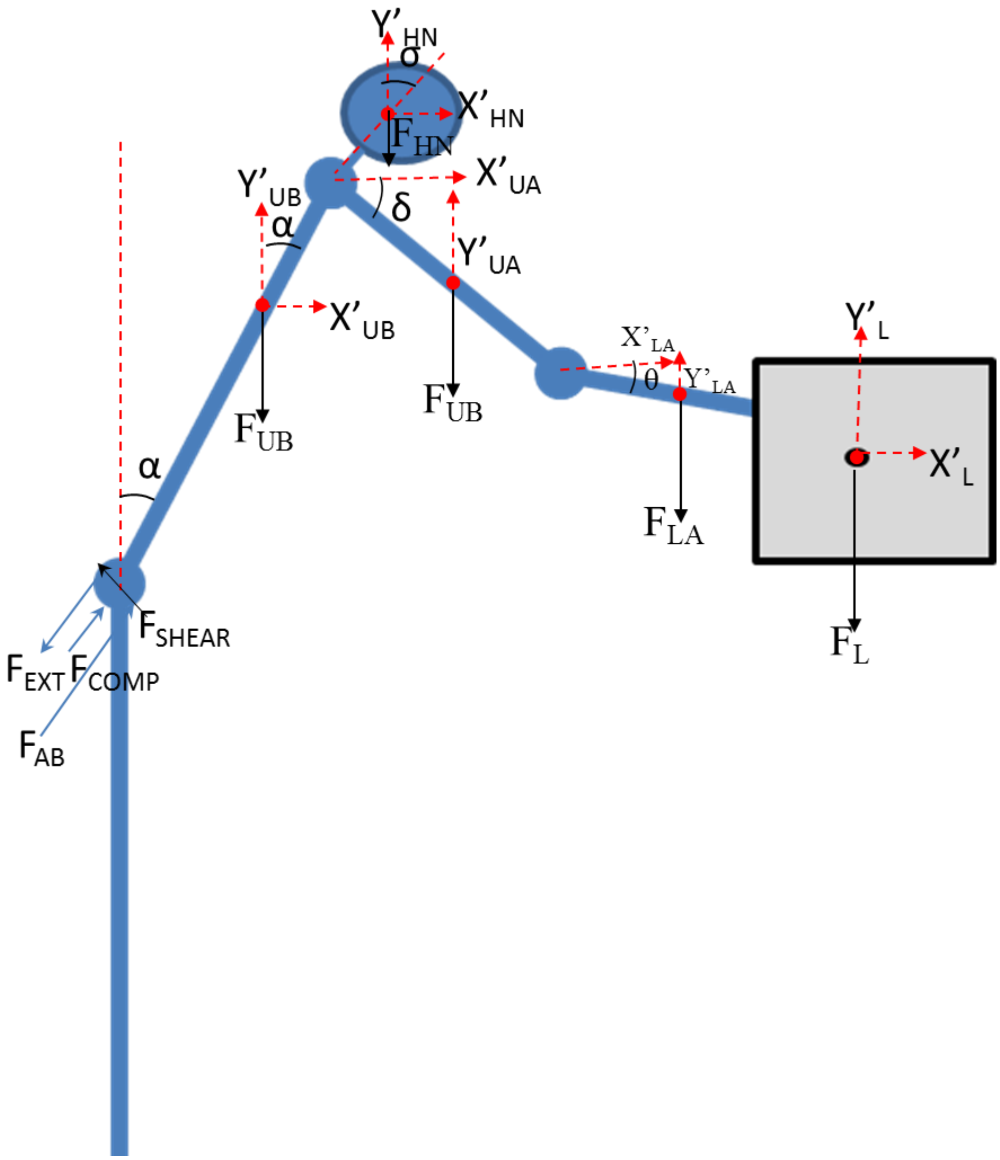


Figure 3.13: Horizontal and vertical displacements and angles of segment centres of mass

$$x'_{UA} = r'_{UA}\ Cos\ \delta$$ Equation 3.31a

$$y'_{UA} = r'_{UA}\ Sin\ \delta$$ Equation 3.31b

$$x'_{LA} = r'_{LA}\ Cos\ \theta$$ Equation 3.31c

$$y'_{LA} = r'_{LA}\ Sin\ \theta$$ Equation 3.31d

$$x'_{HN} = r'_{HN}\ Cos\ \delta$$ Equation 3.31e

$y'_{HN} = r'_{HN}\ Sin\ \delta$ Equation 3.31f

$x'_{UB} = r'_{UB}\ Sin\ \alpha$ Equation 3.31g

$y'_{UB} = r'_{UB}\ Cos\ \alpha$ Equation 3.31h

Change in angular displacement is presented using the following notations and symbols:

$\Delta\alpha = \alpha_2 - \alpha_1$ Equation 3.32a

$\Delta\delta = \delta_2 - \delta_1$ Equation 3.32b

$\Delta\sigma = \sigma_2 - \sigma_1$ Equation 3.32c

$\Delta\theta = \theta_2 - \theta_1$ Equation 3.32d

Displacement Notations Adopted

The following notations have been assigned to the segment parts for ease in mathematical formulation.

r_{UA} = Length of the upper-arm (measured along the segment from the elbow to shoulder joint)

r_{LA} = Length of the lower-arm (measured along the segment from the elbow joint including the hand)

r_{HN} = Length of the head and neck segment (measured along the segment from top of head to the shoulder)

r_{UB} = Length of the upper-back segment (measured along the segment from the shoulder to the hip)

r'_{UA}, r'_{LA}, r'_{UB}, r'_{HN} are the distances from the centre of mass of each segment (upper-arm, lower-arm, upper-back, and head and neck, respectively) to their reference joint measures along the segment.

$x'_{UA} = x'_1$, $x'_{LA} = x'_2$, $y'_{UA} = y'_1$, $y'_{LA} = y'_2$ are the resultant horizontal and vertical displacements of the centre of mass of the upper- and lower-arm to the shoulder. These are also moment arms for the reactive forces.

$x'_{UB} = x'_4$, $x'_{HN} = x'_5$, $y'_{UB} = y'_4$, $y'_{HN} = y'_5$ are the resultant horizontal and vertical displacements of the centre of mass of the upper-back and head and neck segments. These are moment arms for the reactive forces.

δ, θ, σ, and α are angular displacements of the upper-arm, lower-arm, head and neck, and upper-back, respectively. The upper- and lower-arm angles (δ, θ) are measures with respect to the horizontal plane, while the head and neck and upper-back segment angles (σ, α) are measured from the vertical plane.

Δt is the time interval (seconds). This is the duration under study: $\Delta t = t_2 - t_1$.

In all cases, the displacements of the vertical components are + ve in upward displacement and -ve in downward displacement. Also, horizontal (x-plane) displacements are positive if the segment is moving from right to left (upward motion), and negative when moving from left to right (downward motion) (Figure 3.14). The subscripts "1" and "2" represent the initial and current positions, respectively, of the reference length from the centre of mass location.

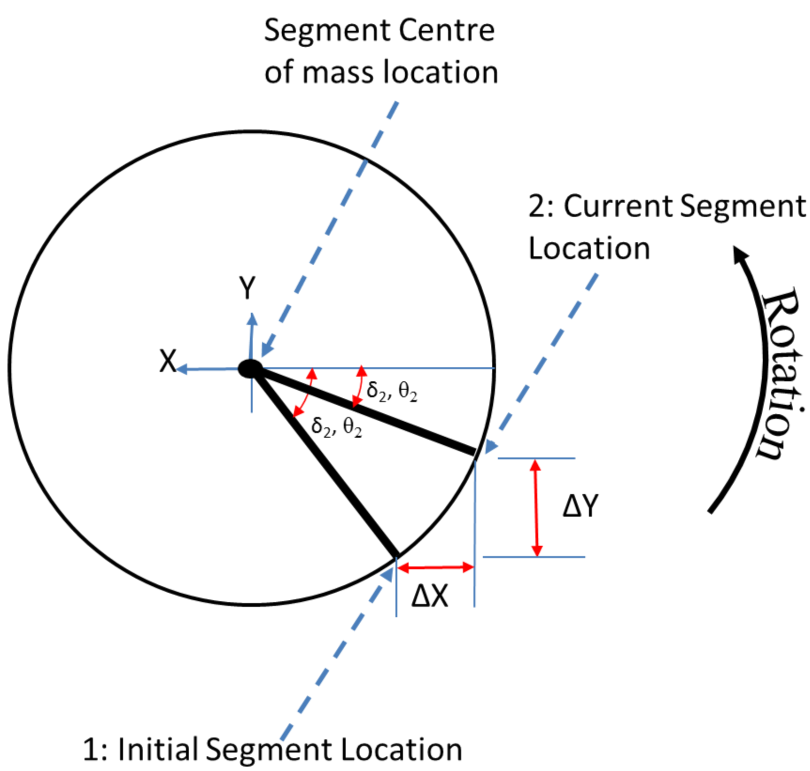


Figure 3.14: Analysis of segment displacement from the centres of mass to reference location

Scenario 4: Lifting and lowering of load from an initial height A to a final height B

Condition (i) Bend, reach to touch load, or bend up to upright posture

For this condition, the upper-back, head and neck, and upper- and lower-arms are displaced from their initial position in the motion to reach to the load. The reactive forces developed are influenced by the acceleration of the segment masses (concentrated at its centre of mass location), which is controlled by the velocities of motion/displacement of each affected segment.

4) Quantifying the linear acceleration and displacement of the body segments for the upper body bending motion involves the assumption of a maximum back flexion of 90^o ($0 \leq \alpha \leq 90^o$) from the vertical plane, as shown in Figure 3.15.

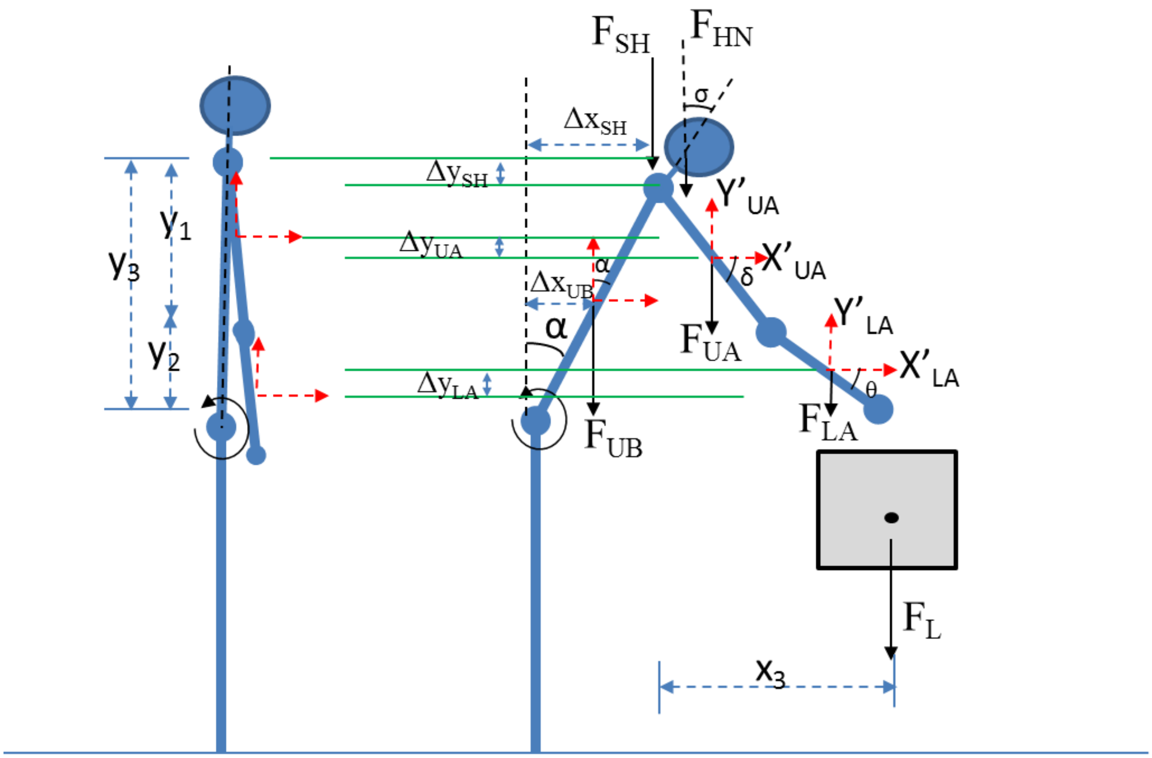


Figure 3.15: Horizontal and vertical displacements and angles of segment centres of mass

(a) UPPER-BACK DISPLACEMENT AND ACCELERATION

$\Delta x'_{UB} = x'_{2UB} - x'_{1UB} = r'_{UB} |\text{Sin } \alpha_2 - \text{Sin } \alpha_1|$ Equation 3.33a

$a'_{UB(x)} = (\Delta x'_{UB} / (\Delta t_{UB})^2)$ Equation 3.33b

$\Delta y'_{UB} = y'_{2UB} - y'_{1UB} = r'_{UB} |\text{Cos } \alpha_2 - \text{Cos } \alpha_1|$ Equation 3.33c

$a'_{UB(y)} = (\Delta y'_{UB} / (\Delta t_{UB})^2)$ Equation 3.33d

Where Δt_{UB} is the time interval of the upper-back movement.

(b) HEAD AND NECK DISPLACEMENT AND ACCELERATION

$\Delta x'_{HN} = \Delta x'_{UB} + x'_{2HN} - x'_{1HN} = \Delta x'_{UB} + r'_{HN} |Sin\ \sigma_2 - Sin\ \sigma_1|$ Equation 3.34a

$a'_{HN(x)} = (\Delta x'_{HN} / (\Delta t_{HN})^2)$ Equation 3.34b

$\Delta y'_{HN} = \Delta y'_{UB} + y'_{2HN} - y'_{1HN} = \Delta y'_{UB +}\ r'_{HN} |Cos\ \alpha_2 - Cos\ \alpha_1|$ Equation 3.34c

$a'_{HN\ (y)} = (\Delta y'_{HN} / (\Delta t_{HN})^2)$ Equation 3.34d

Where Δt_{HN} is the time interval of the head and neck movement.

(c) SHOULDER DISPLACEMENT

$\Delta x'_{SH} = x'_{2SH} - x'_{1SH} = r'_{UB} |Sin\ \alpha_2 - Sin\ \alpha_1|$ Equation 3.35a

$\Delta y'_{SH} = y'_{2SH} - y'_{1SH} = r'_{UB} |Cos\ \alpha_2 - Cos\ \alpha_1|$ Equation 3.35b

Where $y_3 = r_{UB}$ = Length of the upper-back segment measured along the segment from the shoulder to the hip.

(d) UPPER-ARM DISPLACEMENT AND ACCELERATION

$\Delta x'_{UA} = \Delta x'_{SH} + |x'_{2UA} - x'_{1UA}|$ Equation 3.36a

$x'_{2UA} = r'_{UA}\ Cos\ \delta_2$ Equation 3.36b

$x'_{1UA} = r'_{UA}\ Cos\ \delta_1$ Equation 3.36c

$a'_{UA(x)} = (\Delta x'_{UA} / (\Delta t_{UA})^2)$ Equation 3.36d

$y'_{2UA} = r'_{UA}\ Sin\ \delta_2$ Equation 3.36e

$y'_{1UA} = r'_{UA}\ Sin\ \delta_1$ Equation 3.36f

$\Delta y'_{UA} = \Delta y'_{SH} + |y'_{2UA} - y'_{1UA}|$ Equation 3.36g

$\Delta y'_{UA} = |y'_{2SH} - y'_{1SH}| + |y'_{2UA} - y'_{1UA}|$ Equation 3.36h

$a'_{UA(y)} = (\Delta y'_{UA} / (\Delta t_{UA})^2)$ Equation 3.36i

Where Δt_{UA} is the time interval of the upper-arm movement. $a'_{UA(y)}$, $a'_{UA(x)}$ are vertical and horizontal components of linear accelerations due to the motion.

(e) LOWER-ARM DISPLACEMENT AND ACCELERATION

$\Delta x'_{LA} = \Delta x_{UA} + |x'_{2LA} - x'_{1LA}|$ Equation 3.37a

$\Delta x_{UA} = r_{UA} |Cos\ \delta_{2\ -}\ Cos\ \delta_1|$

$x'_{2LA} = r'_{LA}\ Cos\ \theta_2$ Equation 3.37b

$x'_{1LA} = r'_{LA}\ Cos\ \theta_1$ Equation 3.37c

$a'_{LA(x)} = (\Delta x'_{LA} / (\Delta t_{LA})^2)$ Equation 3.37d

$y'_{2LA} = r'_{LA} \sin \theta_2$ Equation 3.37e

$y'_{1LA} = r'_{LA} \sin \theta_1$ Equation 3.37f

$\Delta y'_{LA} = \Delta y_{UA} \pm |y'_{2LA} - y'_{1LA}|$ Equation 3.37g

$\Delta y'_{LA} = |y_{2UA} - y_{1UA}| \pm |y'_{2LA} - y'_{1LA}|$ Equation 3.37h

$|y_{2UA} - y_{1UA}| = r_{UA} |\sin \delta_2 - \sin \delta_1|$

$a'_{LA(y)} = (\Delta y'_{LA} / (\Delta t_{LA})^2)$ Equation 3.37i

Note: The ± sign in Equation 3.37g and 3.37h can be explained as follows. If the lower-arm angle (θ) is above the horizontal plane, then the equation becomes $\Delta y'_{LA} = |y'_{2UA} - y'_{1UA}| - |y'_{2LA} - y'_{1LA}|$. However, if it is below the horizontal plane, then it is written as $\Delta y'_{LA} = |y'_{2UA} - y'_{1UA}| + |y'_{2LA} - y'_{1LA}|$.

Equations 3.33d, 3.34d, 3.36i and 3.37i show that less compressive force will be required when stooping to reach a load. Substituting the above equations into Equation 3.33d to 3.34d will yield the total compressive forces and moments for this activity and posture.

Condition (ii): Lift or lower load from initial height (A) to place at final position (B)

This scenario involves the following:

1. Vertical and horizontal displacement of the load
2. Vertical and horizontal displacement of the upper-arm, lower-arm, shoulder, upper-back, and head and neck segments.
3. Vertical and horizontal component of the linear acceleration of the load during the time interval (Δt_L) as the load is lifted from A to B.
4. Vertical and horizontal components of the linear acceleration of the body segments during the time interval (Δt_i) acting at the centre of gravity of the segment under consideration as the load is lifted from A to B.

For all scenarios of lifting or lowering, displacement and acceleration of the upper-back and head and neck segments involves an upward displacement and acceleration over a time period and thus Equations 3.33a up to and including Equation 3.35b are valid for use in all cases.

However, upper- and lower-arm displacements may involve any of 3 different cases, depending on the final load placement position. These cases can be assessed as follows.

Case 1: load initial position (A) is below shoulder height and load final position (B) is below or at shoulder height (A, B≤ S_H) or vice versa (lifting or lowering of load)

(a) UPPER-ARM DISPLACEMENT AND ACCELERATION

Equations 3.36a to Equation 3.36i apply:

(b) LOWER-ARM DISPLACEMENT AND ACCELERATION

Equations 3.37a to Equation 3.37i apply:

(c) LOAD DISPLACEMENT AND ACCELERATION

For all cases of lifting of load,

$\Delta y'_L$ = Vertical displacement of load

$\Delta x'_L$ = Horizontal displacement of load

$\Delta y'_L = |y'_{2L} - y'_{1L}|$ Equation 3.38a

$a'_L(y) = \Delta y'_L / (\Delta t_L)^2)$ Equation 3.38b

$\Delta x'_L = |x'_{2L} - x'_{1L}|$ Equation 3.38c

$a'_L(x) = \Delta x'_L / (\Delta t_L)^2)$ Equation 3.38d

Case 2: Load initial position (A) is below shoulder height and load final position (B) is above shoulder height ($A \leq S_H$) ($B \geq S_H$) or vice versa (lifting or lowering load)

This case can be assessed as two (2) different time intervals.

1. Angular displacement of the upper-arm to shoulder level (90°)
2. Further angular displacement past the shoulder level as hands are raised above shoulder.

Let $\Sigma\Delta y'_L$ = Total vertical displacement of load; $\Sigma\Delta x'_L$ = Total horizontal displacement of load; If $\Sigma\Delta y'_{UA}$ = Total vertical displacement of the upper-arm; $\Sigma\Delta x'_{UA}$ = Total horizontal displacement of the upper-arm; If $\Sigma\Delta y'_{LA}$ = Total vertical displacement of the lower-arm and $\Sigma\Delta x'_{LA}$ = Total Horizontal displacement of the lower-arm

The displacement up to the shoulder is denoted as (1-2) and above shoulder as (2-3). Hence, y'_{1L}, y'_{1UA}, y'_{1LA} are the initial vertical components of the load, upper-arm and lower-arm positions, respectively, y'_{2L}, y'_{2UA}, y'_{2LA} is the vertical components of load, upper-arm and lower-arm positions, respectively, at or below the shoulder (after initial time interval i) and y'_{3L}, y'_{3UA}, y'_{3LA} is the vertical components of load, upper-arm, and lower-arm positions, respectively, when the load is raised above the shoulder. Consequently, x'_{1L}, x'_{1UA}, x'_{1LA} are the initial horizontal components of the load, upper-arm, and lower-arm positions, respectively, x'_{2L}, x'_{2UA}, x'_{2LA} are the horizontal components of load, upper-arm, and lower-arm positions, respectively, at or below the shoulder (after initial time interval i) and x'_{3L}, x'_{3UA}, x'_{3LA} are the horizontal components of load, upper-arm, and lower-arm positions, respectively, when the load is raised above the shoulder.

(a) TOTAL UPPER-ARM DISPLACEMENT AND ACCELERATION

$\Delta y'_{UA(1\text{-}2)} = |y'_{2UA} - y'_{1UA}|$ Equation 3.39a

$\Delta y'_{UA(2\text{-}3)} = |y'_{3UA} - y'_{2UA}|$ Equation 3.39b

$\Sigma\Delta y'_{UA} = \Delta y'_{UA(1\text{-}2)} + \Delta y'_{UA(2\text{-}3)}$ Equation 3.39c

$a'_{UA}(y) = \Sigma\Delta y'_{UA} / (\Delta t_{UA})^2)$ Equation 3.39d

$\Delta x'_{UA(1\text{-}2)} = |x'_{2UA} - x'_{1UA}|$ Equation 3.39e

$\Delta x'_{UA(2\text{-}3)} = |x'_{3UA} - x'_{2UA}|$ Equation 3.39f

$\Sigma\Delta x'_{UA} = \Delta x'_{UA(1\text{-}2)} + \Delta x'_{UA(2\text{-}3)}$ Equation 3.39g

$a'_{UA}(x) = \Sigma\Delta x'_{UA} / (\Delta t_{UA})^2)$ Equation 3.39h

(b) TOTAL LOWER-ARM DISPLACEMENT AND ACCELERATION

$\Delta y'_{LA(1\text{-}2)} = |y'_{2LA} - y'_{1LA}|$ Equation 3.40a

$\Delta y'_{LA(2\text{-}3)} = |y'_{3LA} - y'_{2LA}|$ Equation 3.40b

$\Sigma\Delta y'_{LA} = \Delta y'_{LA(1\text{-}2)} + \Delta y'_{LA(2\text{-}3)}$ Equation 3.40c

$a'_{LA}(y) = \Sigma\Delta y'_{LA} / (\Delta t_{LA})^2)$ Equation 3.40d

$\Delta x'_{LA(1\text{-}2)} = |x'_{2LA} - x'_{1LA}|$ Equation 3.40e

$\Delta x'_{LA(2\text{-}3)} = |x'_{3LA} - x'_{2LA}|$ Equation 3.40f

$\Sigma\Delta x'_{LA} = \Delta x'_{LA(1\text{-}2)} + \Delta x'_{LA(2\text{-}3)}$ Equation 3.40g

$a'_{LA}(x) = \Sigma\Delta x'_{LA} / (\Delta t_{LA})^2)$ Equation 3.40h

(c) TOTAL LOAD DISPLACEMENT AND ACCELERATION

$\Delta y'_{L(1\text{-}2)} = |y'_{2L} - y'_{1L}|$ Equation 3.41a

$\Delta y'_{L(2\text{-}3)} = |y'_{3L} - y'_{2L}|$ Equation 3.41b

$\Sigma\Delta y'_{L} = \Delta y'_{L(1\text{-}2)} + \Delta y'_{L(2\text{-}3)}$ Equation 3.41c

$a'_{L}(y) = \Sigma\Delta y'_{L} / (\Delta t_{L})^2)$ Equation 3.41d

$\Delta x'_{L(1\text{-}2)} = |x'_{2L} - x'_{1L}|$ Equation 3.41e

$\Delta x'_{L(2\text{-}3)} = |x'_{3L} - x'_{2L}|$ Equation 3.41f

$\Sigma\Delta x'_L = \Delta x'_{L(1-2)} + \Delta x'_{L(2-3)}$ Equation 3.41g

$a'_L(x) = \Sigma\Delta x'_L / (\Delta t_L)^2)$ Equation 3.41h

Case 3: Load Initial position (A) is at or above shoulder height and Load Final position (B) is above shoulder height (A, B ≥ S_H)

(a) UPPER-ARM DISPLACEMENT AND ACCELERATION

Equations 3.36a to Equation 3.36i apply

(b) LOWER-ARM DISPLACEMENT AND ACCELERATION

Equations 3.37a to Equation 3.37i apply

(c) LOAD DISPLACEMENT AND ACCELERATION

Equations 3.38a to Equation 3.38d applies.

Quantifying the cumulative biomechanical stress

Stuebbe et al. (2002) have shown that workers are considered to be at a greater risk of musculoskeletal injury if estimated forces and torques exceed the tissue biomechanical tolerance limits of the worker. An ability to estimate the maximum compressive or shear forces occurring during work would help reduce the exposure to ergonomic risks. Biomechanical analysis allows for a measure of changes in the magnitude of biomechanical stress and variations in work activity. Epidemiological studies indicate that low back pain can cause deterioration of intervertebral discs, facet joints, spine, and ligaments from biomechanical wear and tear. Biomechanical stresses result from either an instantaneous traumatogenesis (fracture, location) or from cumulative pathogenesis (gradual development of a disability or disease through repeated exposure over an extended time period).

Cumulative biomechanical stress (CBS) is the application of biomechanical analysis throughout the work cycle or work shift for the purpose of estimating work load. It measures the changes in magnitude of biomechanical stress (compressive and shear) in a manner more accurately representing work activity. This technique of applying biomechanics to quantify cumulative load from work, however, has been largely ignored. Occupational activities are designed to meet occupational productivity demands and not to optimize for biological compatibility. In order to be of any economic importance, work tasks are designed to be repetitive (the frequency of repetition varies from one job or task to another depending on the number of activities involved) and as such they employ a number of muscles at various joints. Asymmetric motions are very frequent with repetitive activities, and are thus common in construction and other industries (Garg and Badger 1986; McGill 1991).

Kumar (2001) presented the "*cumulative load theory*" which states that musculoskeletal tissues, like other physical materials, have a definite life. Although they are capable of self-repair, they are subject to mechanical degradation (wear and tear) as a result of prolonged or repeated use. Repeated load application leads to cumulative fatigue and reduction of the stress-bearing capacity, which may further reduce the stress threshold for failure. Kumar's earlier work (1990) reported a strong correlation between the cumulative biomechanical load and exposure time integral (over an entire work life) with lower-back pain/injury ($p<0.01$) based on an assessment of compression and shear load on the spine. Kumar (2001) applied this knowledge to a case study of male and female nursing aides grouped based on reported LBP "*pain group*" and no reported pain "*no-pain group*". The results of the study show no significant difference between the *pain* and *no-pain* groups in any of the biomechanical spinal load variables when compared for one cycle; however, the *cumulative load time* (total time spent working in the activity) was higher for the *pain group* than for the *no-pain group.* The *cumulative load time* was calculated by summing the load time product (N.s) and multiplying the sum by the number of cycles performed on a shift to obtain the cumulative load during each shift for both compression and shear (Kumar 2001).

Three (3) techniques have been recorded in ergonomics research for assessing the cumulative biomechanical stress resulting from work activities. According to Keyserling et al. (1987),

$$CSC = \sum_{i=1}^{n} (T_i \text{ X } S_{Ci}) \qquad \text{Equation 3.42a}$$

Where: CSC = cumulative spinal compression (Ns); T_i = time spent in posture i(s); S_{Ci} = Spinal compression in posture i(N); n = number of different posture classification categories.

Kumar (1990) used an assessment of critical working postures, forces, and their respective frequencies to determine daily cumulative load, compression, or shear.

$$CDC_o = \sum_{i=1}^{n} (MC_{oi} \text{ X } F_i) \qquad \text{Equation 3.42b}$$

Where: CDC_o = cumulative daily overall compression for tasks i-n (Ns); MC_{oi} = spinal compression from load, M, for task i (N); F_i = frequency per day for task i(s); n = number of different tasks performed.

Stuebbe et al. (2002) developed an equation to estimate the cumulative weekly, monthly, and yearly loads from daily load on the basis of 5 or 6 days per work week, 4 weeks per month, 12 months per year. This can also be applied to estimate the lifetime cumulative biomechanical stress exposure from work activities.

$C_{BL} = = \sum_{i=1}^{n}(C_i)$ Equation 3.42c

Where: C_{BL} = cumulative spinal compression (N) per 8 hrs; C_i = spinal compression for observation i(N); n = number of work sampling observations

Based on the above research, the cumulative compression or shear forces can be determined using:

$CF_{COMP} = \sum_{i=1}^{n}(F_{COMP} \text{ X } (F_i \text{ X } T_i)$ Equation 3.43a

$CF_{SHEAR} = \sum_{i=1}^{n}(F_{SHEAR} \text{ X } (F_i \text{ X } T_i)$ Equation 3.43b

Where: CF_{COMP} = cumulative compressive stress (Ns); CF_{SHEAR} = cumulative shear stress (Ns); F_{COMP} = Lower-back compressive force from activity i(N); F_{SHEAR} = lower-back shear force for activity i(N); F_i = Frequency of activity per day; T_i = Duration (cycle time) of activity i (s)

3.2.3 Discrete event simulation application for ergonomic assessment

Ergonomic field studies, though reliable, are hampered by high employee turnover (Nussbaum et al. 2009). They may also be costly and require long periods of observation in order to attain statistical acceptance. By applying the advantages of computer simulation and visualization, the real world and "what if" scenarios can be modelled and analyzed. The proposed methodology is developed accordingly in three parts as represented in Figure 3.16.

Part 1: Database Design: A Microsoft Access database is designed to store duration and productivity information (work rates, equipment productivity) and activity details (including physical demand assessment information). Input data such as task information, specifications, activities, execution sequence, duration, tools and equipment required in designing the hierarchy, and process interaction are collected and used for database design.

Part 2: Process Simulation – Discrete event simulation of work process: Work sequence and observational data are applied in order to validate the logical interactions necessary in designing the simulation process using Simphony. The process simulation is activity-based. For each selected activity, since all the relevant information has been stored in the database, a body part (segment)-based discrete event simulation is developed based on Simphony's general template. The simulation model is incorporated with the database as its source for physical demand and productivity data. Also, the developed model is designed with data-exporting functionality. The output provides a detailed step-by-step sequence and task execution process with duration and activity information. The output from the simulation run can be assessed to determine the level of ergonomic risk exposure. Multiple scenarios can be incorporated to embellish the model or review different recommendations aimed at reducing or eliminating risk. This is used to inform recommendations for redesign.

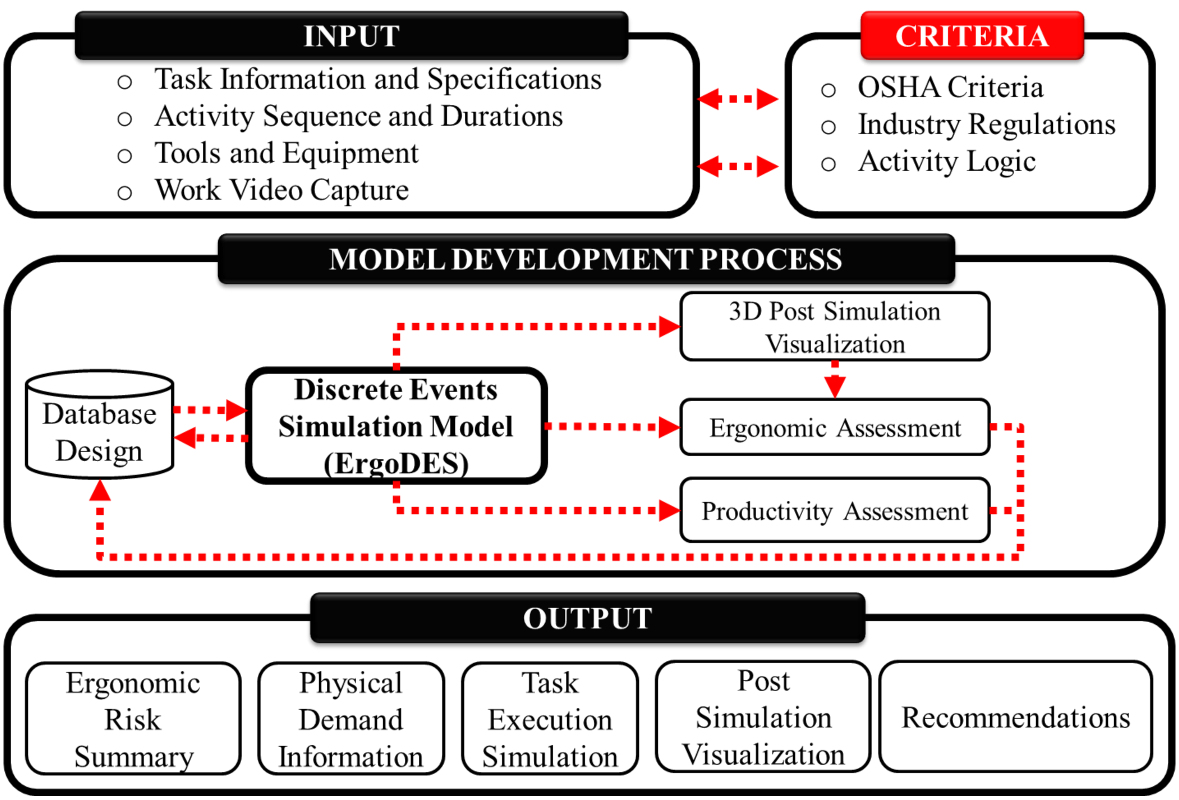


Figure 3.16: Methodology of ergonomics Discrete Event Simulation Model Development

Part 3: Visualization: Depending on the need, a post simulation visualization model of the simulated task can be developed using the simulation output.

3.2.4 Proposed Fatigue-Productivity Relationship model

Resource-based productivity assesses the output with respect to input (Equation 2.8). The output is measured by the power expended, the amount of work done, the task completed, or the distance travelled, while input may be in terms of man hours per day, strength, or muscle force generated to accomplish task. A decline in the power output can be interpreted as a loss in productivity, while a drop in muscle strength or capacity signifies fatigue. It is known that an individual can sustain effort under repetitive or non-repetitive exposure for some time (t) before visible signs of fatigue set in. An understanding of productivity and conservation of energy and power will be applied with the dynamic fatigue model developed by Ma et al. (2009) to predict productivity relationship with fatigue. This model is based on the following theory:

> *Muscle fatigue and, consequently, a reduction in muscle force (maximum contraction force) will continue unnoticed up until the point at which the available power (based on current maximum muscle force –$F_{CEM}(t)$) is less than the actual force (F_{ACT}) required to perform the activity at its current rate. At this point, the central nervous system will adjust the work rate in order to allow the muscle to perform the activity safely. This will result in a time increment for performing the same task (same activity takes a longer amount of time to accomplish), indicating a loss of muscle productivity such that, if continued without sufficient rest and recovery, the productivity decline will become more pronounced, leading to exhaustion."* (see Figure 3.17).

According to Kumar's *theory of differential fatigue* (2001), a particular task may involve several activities, each presenting different physical demands (differential loading) on the worker, and each executed in different postures. Since each activity consumes energy differently, (as shown by the metabolic energy cost assessments), the muscle fatigue rates will be different for each activity.

This research focuses on ergonomic risks resulting from exposure to physiological and biomechanical risks from physical exertion of muscle force under different postural ranges and tool uses. Work productivity is correlated to the amount of energy expended to do work, and the development of local muscle fatigue has been related in the reviewed literature (Section 2.5) to the amount of energy expended in doing work. An event-based productivity-fatigue relationship as illustrated by Figure 3.17 is proposed based on the theory of differential fatigue offered by Kumar (2001) as well as the dynamic fatigue model described by Ma et al. (2010) (P_0 is initial productivity, P_i, P_{i+1} represent productivity at each step interval, t_0, t_i and t_{i+1} represent duration taken to accomplish activity at each time step). This relationship attempts to explain the effect of muscular fatigue on worker productivity based on the philosophy that the fatigue state of the limiting muscle group controls productivity. Detailed model equations supporting this theory are presented in Equations 3.44-3.55.

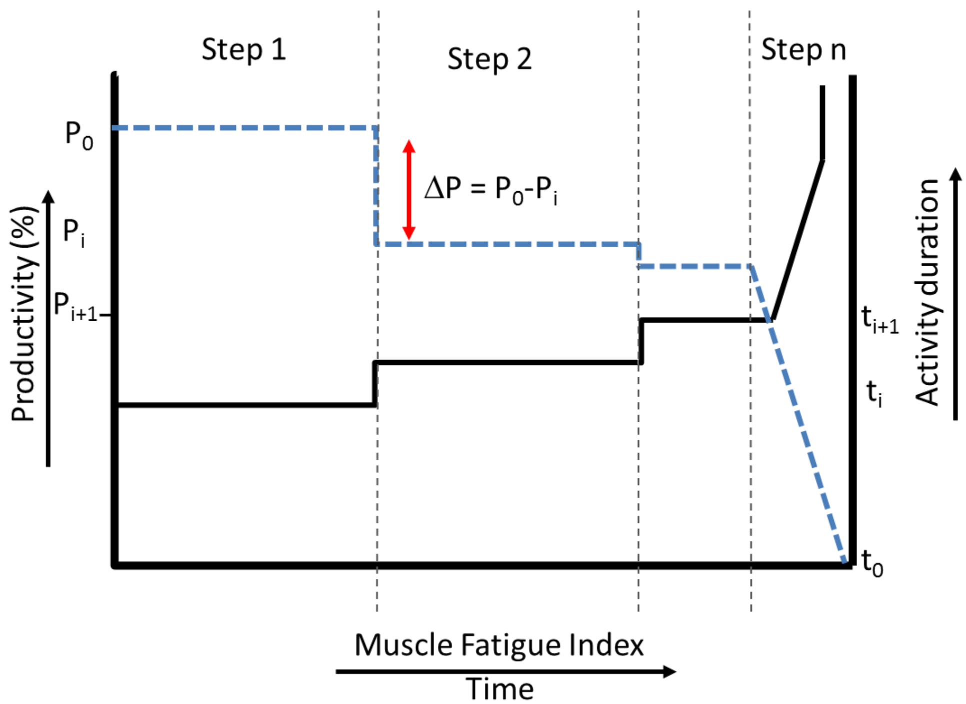


Figure 3.17: Event-based fatigue-productivity relationship

Development of Proposed Productivity-Fatigue Relationship Model

$$\text{Productivity} = \frac{Output}{Input} \qquad \text{Eqn. 3.44}$$

Where: Output = Work to be done, Input = Time to accomplish work

Also, Power is the rate at which work is done.

$$\text{Power} = \frac{Work}{Time} \qquad \text{Eqn. 3.45}$$

It can be seen from Equations 3.44 and 3.45 that resource-based productivity is equivalent to the power (or energy) expended to perform an assigned activity (Equation 3.46).

Power ≡ Productivity Eqn. 3.46

Also, the work accomplished is the product of the force expended and the distance moved by the force, as presented by Equation 3.47.

Work = F_{ACT} X D_{ACT} Eqn. 3.47

Where F_{ACT} is the actual force expended to perform the activity and D_{ACT} is the distance moved by force.

For a particular activity executed under the same conditions, the distance and required force are constant, since the actual work is constant. However, the rate at which the work is done (power) may vary.

The level of fatigue and productivity of muscles recruited to perform an activity can be assessed as an event-based process. Using this technique, at different activity events, the force-producing capacity of the muscles with respect to the Maximum Voluntary Contraction (MVC) force and the ability to maintain the same work pace (constant rate and force expenditure) are assessed.

At the beginning of the task, assuming work is started from an initial rested state, the muscle's maximum force available to perform an activity is equal to its MVC (F_{MVC}). However, to accomplish an activity, A, the actual muscle force expended (F_{ACT}) to accomplish the activity within duration (t_i) will only be a percentage of F_{MVC} ($F_{ACT} = \%F_{MVC}$). This will result in a reduction in F_{MVC} according to the definition of relative force (F_{REL}).

As long as the maximum voluntary force/strength of the muscle for the posture and physical demand of the task is greater than that generated in performing the task at the default rate, the work will be performed at that steady productivity level. Thus, the actual power expended (P_{ACT}) by the muscle to perform the activity at the current rate can be represented by (Equation 3.48).

Discrete Productivity Impact Model

Power (P_i) = WD_i/t_i

$\therefore WD_i = P_i \text{ x } t_i$ Eqn. 3.48

At time t_2 in order to accomplish the same task (event), Power (P_{i+1}) = WD_{i+1}/t_{i+1}

$\therefore WD_{i+1} = P_{i+1} \times t_{i+1}$ Eqn. 3.49

For every task, the central nervous system determines the power to be expended to perform an activity. Assuming there is sufficient muscle strength (MVC) greater than that required to perform the task, based on the design work pace/rate (organizational factor) and productivity targeted, the muscles will generate sufficient force to perform the task at the current rate ($P = F_{ACT} \times D_{ACT}/t_i$). This is the default mean working rate, and it will determine the worker's daily output.

Since the task is the same and is executed under the same condition, $WD_i = WD_{i+1}$

Thus, Equation 3.48 is equal to Equation 3.49, as shown below:

$P_i \times t_i = P_{i+1} \times t_{i+1}$

$t_{i+1} = P_i \times t_i / P_{i+1}$ Eqn. 3.50

$P_i/P_{i+1} = t_{i+1}/t_i$ Eqn. 3.51

Since P_i=P_{i+1} in Equation 3.50, $t_{i+1} = t_i$

However, if, due to fatigue, the current maximum force (F_{CEM}) and, consequently, the power output of the muscle in that posture or activity are less than the default power required (P_{ACT}) to perform the task at the initial work rate, the muscle can only perform the task safely by generating force or power equal to or less than its current MVC (F_{CEM}). Thus, the power available (P_{ACT}) expended at the initial rate will be less than the initial power expended. This power is thus insufficient to perform the required task ($P_{i+1} < P_i$).

Since ($P_{i+1} < P_i$), from Equation 3.50 it can be deduced that the required duration to accomplish the task t_{i+1} is greater than t_i ($t_{i+1} > t_i$). An increase in the task duration signifies a reduction in productivity. This can also be explained using Equation 3.49. Since the work to be done does not change in order to accomplish the same task ($WD_{i+1} = WD_i$), the time t_{i+1} has to be increased since the current power P_{i+1} is less than P_i.

As presented in Equations 3.46 to 3.51, the effect on productivity is not evident until $P_{CEM} < P_{ACT,}$ at which point the current maximum force capacity (F_{CEM}) determines the work rate. This explains the steps in time and, consequently, the productivity in Figure 3.17. Note that the organizational risk factors (especially the ability of the worker to control the task pace) may influence the actual force expended to execute the activity, in which case F_{ACT} may be less than F_{CEM}. Also, rest may not be needed until the point at which $F_{ACT} > F_{CEM}$ for any muscle group, as this is where the effect on productivity becomes visible and the risk of injury is increased. (t=task duration (min). Figure 3.17 also shows that beyond a certain fatigue index, exhaustion sets in.

Continuous Productivity Impact Model

A continuous model has also been developed for the productivity assessment. This is a limiting case as the duration of the work activity, dt, tends toward zero (dt-0).

By virtue of the conservation principle of work, (that is productivity), the following can be written:

P(t) x t = P(t+dt) x (t + dt) Eqn.3.52

The above equation indirectly expresses the idea that if a given task is performed over a longer period of time, the required power from the muscles should be smaller. Applying the Taylor expansion, one can write:

P(t) x t = [P(t) + P'(t) d t] (t + d t)

= P(t) t + P(t) x dt + P'(t) x t x dt + P'(t) (dt)^2 Eqn. 3.53

After simplification, and neglecting quadratic and higher-order terms, one obtains the following differential equation:

dP(t)/P(t) = (d t) / t subjected to the constraint $P(t_0) = P_0$ Eqn. 3.54

Solving the above differential equation yields,

Ln(P) = Ln(t) + C ➔ P(t) = lambda / t Eqn.3.55

Since at t_0, the power is p_0, the constant lambda is calculated as lambda = P_0 t_0

Here it is important to note that the variable, t, represents the range of time during which muscular power is exerted to perform a given task. In other words, it is clear that if one is required to perform a given task instantaneously, that is t=0, it would require a colossal amount of power.

The model equation presented can be used to predict productivity of workers engaged in a construction task by assessing the physiological requirements of the task and muscle strength requirements based on the posture and external load. Applying this model with the dynamic muscle fatigue and recovery model, the occurrence and level (index) of fatigue and its impact on productivity can be assessed. Such knowledge will assist in the design of safe tasks which do not result in excessive fatigue and will help to prevent productivity loss or exhaustion. This proposed model needs experimental validation in order to ascertain the fatigue indices at which the productivity drops are experienced. This validation has not yet been conducted. However, the dynamic muscle fatigue assessment and recovery-based model developed by Ma et al. (2009; 2010) has been validated.

Chapter 4 Case Studies

The current legislation in most Canadian provinces recommends ergonomic assessments only after a worker has reported work-related musculoskeletal disorder (WRMSD) symptom(s). This approach is not proactive, as workers do not generally report potential ergonomic risks until an injury symptom or disability has occurred. Also, most commonly applied ergonomic analysis models report a general summary of task risk classification without specifying the activity controlling the risk and the degree of risk exposure of each body part.

This chapter presents case studies designed and tested using the wall and floor framing process adopted by collaborating Edmonton-based residential builder, Landmark Building Solutions. Study data is extracted from video observations obtained from the factory operations. Landmark Building Solutions delivers high quality housing solutions for the Calgary, Edmonton, and Red Deer markets in Alberta. Building panels are framed using the manufacturing production line process at its Edmonton plant.

Five case studies are presented showing applications of three ergonomic analysis frameworks: (i) checklists, surveys, and reports; (ii) observation-based techniques; and (iii) computer-based techniques. The described cases studies have been conducted over a two-year period (July 2010-August 2012). Video and anthropometric data were taken by the company management after conducting an occupational health and safety seminar and receiving signed consent by the workers, (thus no ethics review or consent was required on the part of the researcher). In accordance with privacy concerns, employee personal details have been removed from the data. These studies were aimed at assessing the actual or potential ergonomic risk from work activities with the goal of improving work methods and equipment. Whenever possible (based on the camera's line of sight), in order to eliminate the negative impact of video observations, the camera was positioned out of sight of the observed worker.

4.1 Organization of Case Studies

The case studies have been organized as follows:

(i) Checklist, Surveys and Reports

Case 1: Shortcomings of reactive ergonomic legislation

In order to determine the success of existing ergonomics practices in the construction industry, a case study was carried out at a residential construction manufacturing plant in Edmonton, Alberta. A self- report checklist was distributed to residential construction framing carpenters in Edmonton, Alberta. Based on the reports of the workers, an assessment of exposure to ergonomic hazard from daily work tasks is presented. This assessment was conducted to test the efficacy of the reactive approach to ergonomic risk reporting as described in Section 2.3.

(ii) Observation-Based Techniques: Two case studies are presented to show the application and validity of the new observation-based ergonomic analysis model, ErgoCheck

(a) Case 2: ErgoCheck-A new observation-based ergonomic analysis model.

This case study was designed to test the new ErgoCheck model for its suitability and accuracy in assessing ergonomic risks. Also, the risk reports are compared with popular ergonomic analysis models—Rapid Entire Body Assessment (REBA) and Rapid Upper Limb Assessment (RULA)—to test compliance and assess the quality of information presented by the new model.

(b) Case 3: A comparison of the ErgoCheck model with REBA and QEC models.

The ErgoCkeck model is further validated by comparing its risk summary with those of REBA and Quick Ergonomic Check (QEC). Correlation of the new model with the QEC and REBA models are also presented.

(a) Computer-based techniques: Two case studies are presented here to assess the applicability and validity of the computer techniques proposed in Sections 3.2.3 and 3.2.4.

(b) Case 4: Biomechanical assessment of lower-back compression and shear stress from wall framing residential construction tasks

The applicability and validity of the biomechanical model developed in Section 3.2.3 for assessing dynamic compression and shear stresses from daily construction tasks is assessed by evaluating wall framing activities in a residential construction factory. This assessment focuses on the lifting, carrying, and lowering tasks identified as major demanding duties of the observed carpenters. The results of this model are validated by comparison with the 3d Static Strength Prediction Program (3DSSPP) and an ErgoCheck assessment of the selected task.

(c) Case 5: Discrete event simulation for ergonomic assessment of construction tasks

The application of discrete event simulation, discussed in Section 3.2.4 in assessing and quantifying ergonomics hazard, is also presented in this case study. This study focuses mainly on postural risk from the assessed wall framing activities. Based on the results, recommendations are applied to redesign the wall framing production line (work station). A re-evaluation with the applied recommendations reviews the impact on ergonomic risk and the productivity of the workers.

4.1 Checklist, Survey, and Report Technique - Shortcomings

Case 1: Shortcomings of reactive ergonomic legislation

Study overview

An ergonomics assessment checklist (Appendix D1) was presented to the workers as a means of job evaluation. As discussed above, the company being examined employs the offsite construction method to manufacture wood framing of residential building panels for the construction of two-storey single family dwellings. The average daily output of the factory is two buildings per day. The factory is comprised of four major work sections: interior wall framing, exterior wall framing, floor framing, and finishing sections. Each of these sections is comprised of work stations and crews. Observations were conducted from July 26th – August 31st, 2010.

The factory operates two work shifts, the morning shift, 7:00am to 4:30 pm, and the evening shift, 4:30 pm to 2:00 am, daily from Monday to Friday. The working day includes one paid 30-minute break and two 15-minute coffee breaks. The panels are constructed in the manufacturing shop and, depending on the building model, spray insulation is applied to the exterior walls. These panels are then loaded onto a trailer and delivered to the construction site using trailers. This method of construction is different from conventional onsite framing and somewhat similar to the modular wood framing construction method, thus presenting ergonomics opportunities and challenges as a result of the work sequence, plant layout, and work station design. Existing ergonomics policies implemented by the company were reviewed. These policies were found to be basically aligned with the Alberta Occupational Health and Safety (OHS) Act and Workers Compensation Board (WCB) guidelines for safe practices. In the previous three years, records of the company's WCB injury and illness claims records were reviewed for reported incidents of WRMSDs. These records showed mostly reports and Lost Time Claims (LTCs) due to accidents, cuts, and falls, with little evidence of Cumulative Trauma Disorders (CTDs) or other musculoskeletal injuries complaints other than two cases of sprain injuries related to fall accidents. This gave the impression that the workers were not exposed to any ergonomic hazards or were not experiencing any of the related symptoms. This impression, however, may be due to the prevalent perception that the majority of musculoskeletal injury symptoms are just typical aches and pains. In this case, workers were given an introduction in ergonomics education prior to administration of the ergonomics analysis survey/checklist (Appendix D1). This is the same checklist used by the Alberta Workplace Health and Safety Board, and it was selected based on the following factors:

- it addresses specific risk factors identified in the scientific literature as being related to materials handling injuries;
- it presents specific exposure limits (times and angles) for worker exposure to risk factors;
- it is relatively simple to understand and can be applied by both employers and workers; and
- it is based on a multi-year literature review and public consultation process that has involved industry, labour, and the public.

Methodology - Self-Reported Ergonomic Hazard Assessment

The assessment checklist administered to the participants included questions regarding job task perceptions, work history, and anthropometric information. The field of subjects for the study included eight (8) exterior wall framing carpenters, three (3) interior framing carpenters, two (2) window installers, one (1) forklift operator, two (2) spray foam operators, one (1) finishing carpenter, one (1) chamfer (a worker who uses the chamfer beveller to make edges connecting two framing surfaces, usually at angles), one (1) layout specialist, and one (1) shift supervisor. These were all full-time workers working for an average of nine (9) hours per day. All participants were male, and ranged in age from 20 to 55 years. Figure 4.1 and Figure 4.2 show the daily work activities, and Table 4.1 shows the workers' basic anthropometric information.

The monitoring was categorized according to the following five (5) ergonomics risk factors

i. Awkward postures: Shoulder, neck, back, or knee postures maintained for four (4) or more hours during a normal day shift (Figure 4.1).
ii. Repetition: Daily tasks requiring repeated neck, shoulder, elbow, or wrist use repeatedly for more than six (6) hours per day without other risk factors or for more than two (2) hours daily with wrist bent in flexion >30°, extension >45°, or ulnar deviation >30° plus high forceful hand exertions.
iii. Repeated impact: Conditions requiring the use of the heel/base of palm as hammer > once per minute, >2 hours total/day or use of knee as hammer > once per minute, 2 hours total/day.
iv. Lifting hazard: Lifting hazards were assessed based on the average weights lifted by the worker, the frequency of lifts, and position of the worker's hands while performing the lift (Figure 4.2b).
v. Hand forces: Conditions involving arms, wrist, hands pinching or gripping unsupported objects—either repeatedly, with wrist bent in flexion >30° or extension > 45°, or ulnar deviation >30^o >3hrs/day—for more than three (3) or four (4) hours a day with or without other risk factors, such as awkward postures, repetition, repeated impact, and lifting hazards (Figure 4.2a,b). Hand force is also exerted in the residential construction framing factory while steadying or guiding wall panels during crane lifts, either from assembly line to finishing booth (form spray finish) or loading onto the trailer; it is also used for pulling out nails et cetera (Figure 4.2c,d).

Fig. 4.1.1(a): Hands over head or elbows above shoulders for more than 4 hours per day

Fig. 4.1.1(b): Neck bent more than 30° more than 4 hours per day

Fig. 4.1.1(c): Squatting or kneeling for more than 4 hrs/day

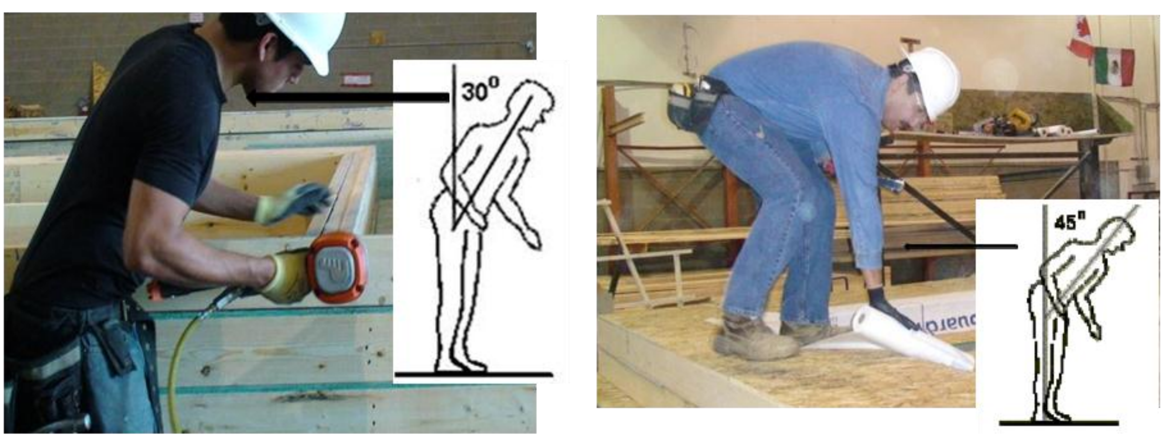
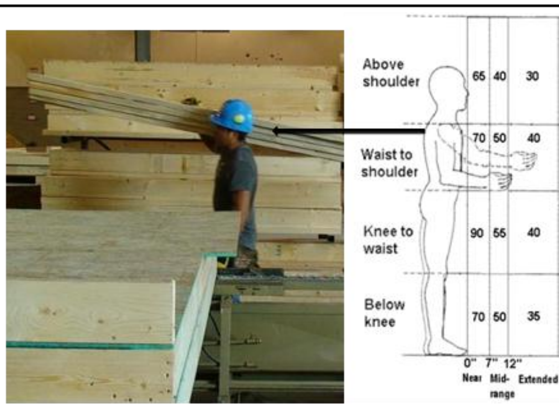


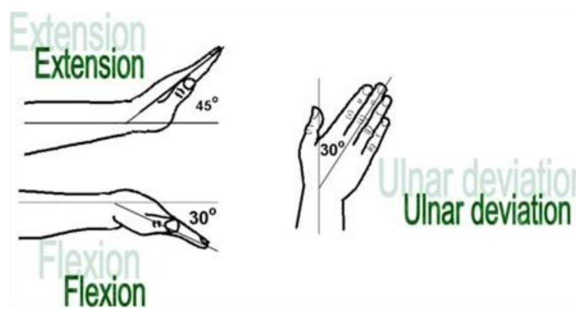
Fig. 4.1.1(d): Back bent more than 30° for more than 4 hrs/day

Figure 4.1: Daily Residential Construction Framing activities

(a): Hand Force: Gripping (10lbs) or pinching (2lbs) more than 3 hours total per day



(b): Lifting: Frequent and or awkward lifting



(c): Wrists Bent in flexion, extension or ulnar deviation for more than 4 hours daily

(d): Hand Force: Countering force, and tool use

Figure 4.2: Daily Residential Construction Framing activities

Results of the Self-Reported Assessment

A self-reporting checklist survey was compiled; the following information was extracted based on each of the ergonomic hazard classes.

Awkward postures:

- Except for the finishing carpenter, all respondents checked off daily exposure to postures involving bending the neck > 45^o for > 4 hours total (Figure 4.3).
- Interior wall framers, window installers, forklift operator, spray foam operators and chamfers all indicated postures involving raising of the hand over the head or elbow for more than a total of 4 hours daily (Figure 4.3).
- Postures requiring the back to be bent >30^o in excess of 4 hours daily was checked by all the workers except the chamfer and interior framing carpenters ,who checked no exposure and varied exposures, respectively (Figure 4.3).
- Daily ergonomic hazards affecting the back and knee was checked off by all exterior wall framing carpenters, window installers, forklift operator, spray foam operators, finishing carpenter, layout specialist, and 2 interior wall framing carpenters (Figure 4.4).
- The window installers, interior wall framers, chamfer, forklift, and spray-foam operators checked off repeated kneeling hazard for more than 4 hours daily.

Hand Force:

- Figure 4.5 shows that interior wall framers, window operators, chamfer, and layout specialist are exposed to hand, wrist, and arm tasks involving gripping of unsupported objects for more than 4 hours per day.
- All respondents except 4 of the exterior wall framers, the finishing carpenters, and shift supervisor checked off daily tasks requiring that the wrist be bent in flexion > 30° or in extension > 45° or with an ulnar deviation > 30° for more than 3 hours total.
- The interior framing carpenters, window installers, spray foam operators, layout specialist, and 6 exterior wall framers reported daily tasks involving arms, wrist, and hand-use involving pinching of unsupported objects (Figure 4.6).

Repetition:

- Figure 4.7 shows that the window installers, forklift operator, spray foam operators, chamfer, and layout specialist indicated repetitive tasks involving neck, shoulder, elbow with wrist bent in flexion > 30° or extension > 45° or ulnar deviation > 30°, plus high forceful hand exertions > 3 hours per day.

Repeated Impact:

- Figure 4.8 shows that repeated impact involving use of the heel/base of the palm as a hammer > once per minute > 2 hours total per day was checked of as a daily hazard by the interior wall framing carpenters, window installers, forklift operator, layout specialist, and 6 of the exterior wall framers.

Based on the results from the checklist administered to the workers, the majority graded their job tasks within the hazard zone for ergonomic risk. A correlation between the results from the assessment of perceived hazard exposure and the results from onsite observation (Figure 4.1 and Figure 4.2) confirms that the majority of the participants are working within the hazardous range for WRMSDs. The results presented here are from self-reporting by the workers and thus they give an idea of what the workers perceive to be the nature of their daily job exposures. It should be noted that the lifting assessment results were not very reliable and so were removed from this analysis due to inconsistency and perceived lack of understanding of the checklist questions. This is one of the disadvantages of self-reported checklists and surveys.

Table 4.1: Workers anthropometric data (Self-Reported)

Job Category	**No of workers**	Age (Yrs)	Ave. Age (yrs)	Mean Height (cm)
Exterior Wall Framing	8	25 25 45 55 45 25 25 20	33	177.4
Interiors Wall framing	3	45 35 35	38	174.3
Holestoffer	1	25	25	
Window Installation	1	55	55	173.0
Forklift Operator	1	35	35	185.3
Sprayfoam	2	35 25	30	178.0
Shamfer	1			
Finishing Carpenter	1	55	55	192.9
Asst Plant manager	1	35	35	188.1
Layout Specialist	1	25	25	182.9
Total:	20			

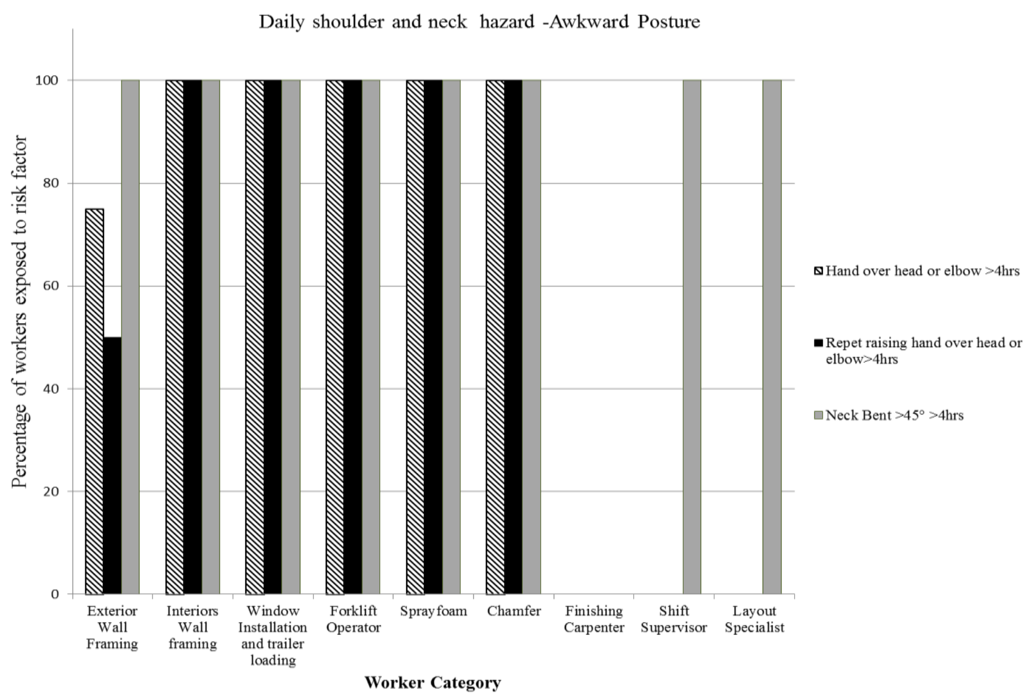


Figure 4.3: Percentage of workers indicating daily exposure to awkward shoulder and neck postures

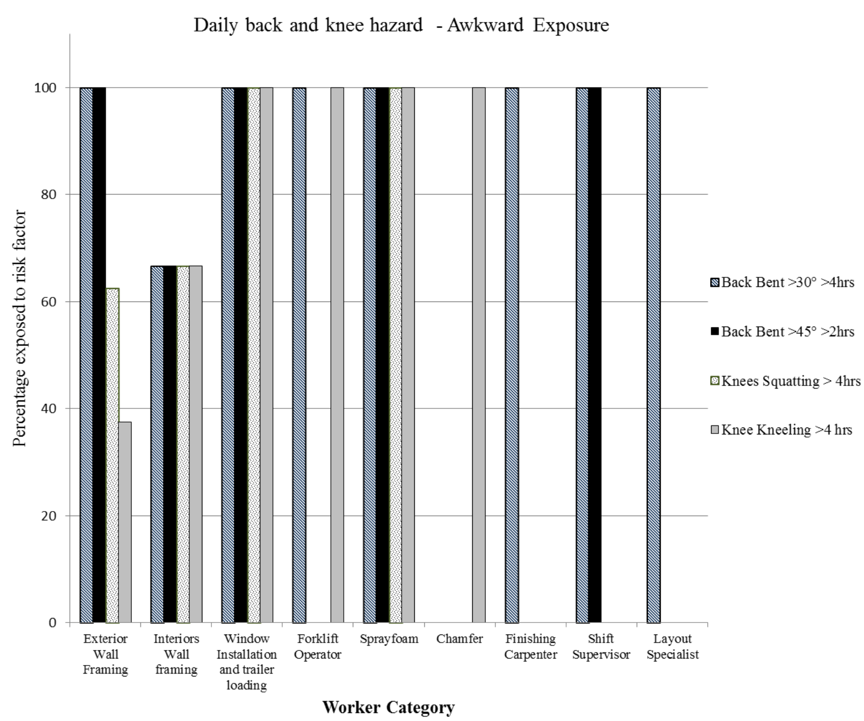


Figure 4.4: Percentage of workers indicating daily exposure to awkward back and knee postures

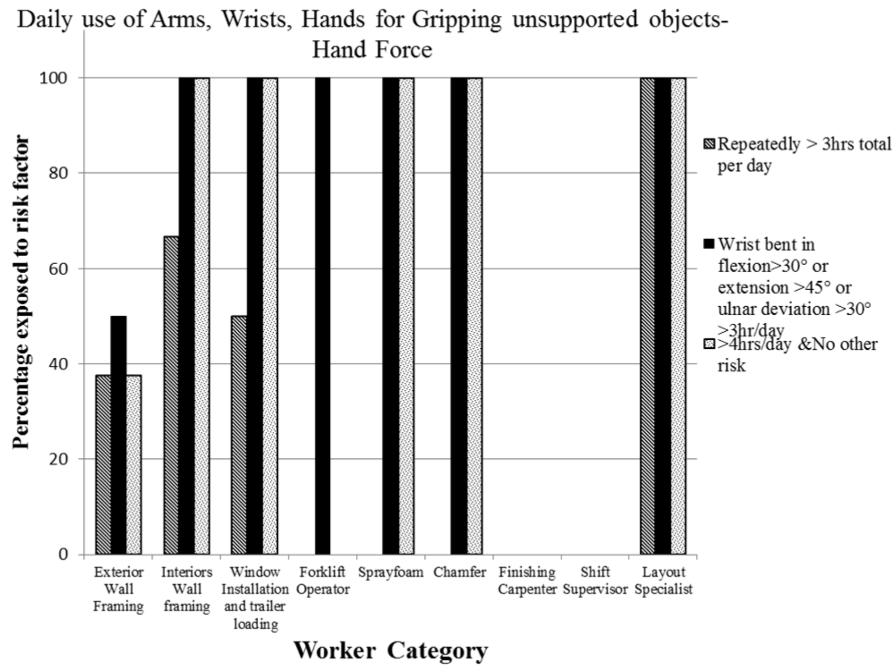


Figure 4.5: Percentage of workers indicating daily exposure to awkward back and knee postures

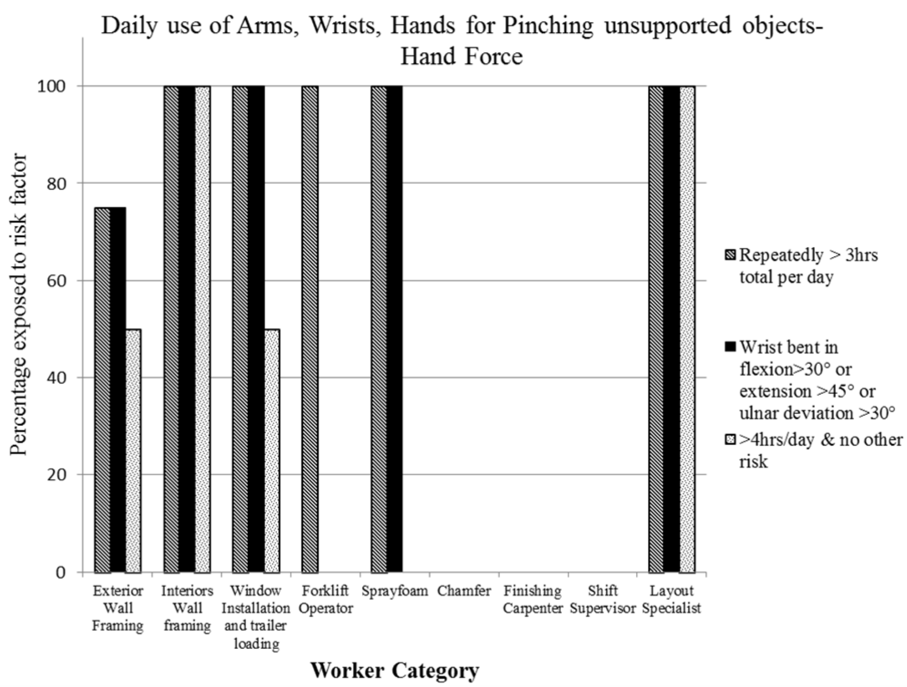


Figure 4.6: Percentage of workers indicating exposure to Hand force hazard-Pinching

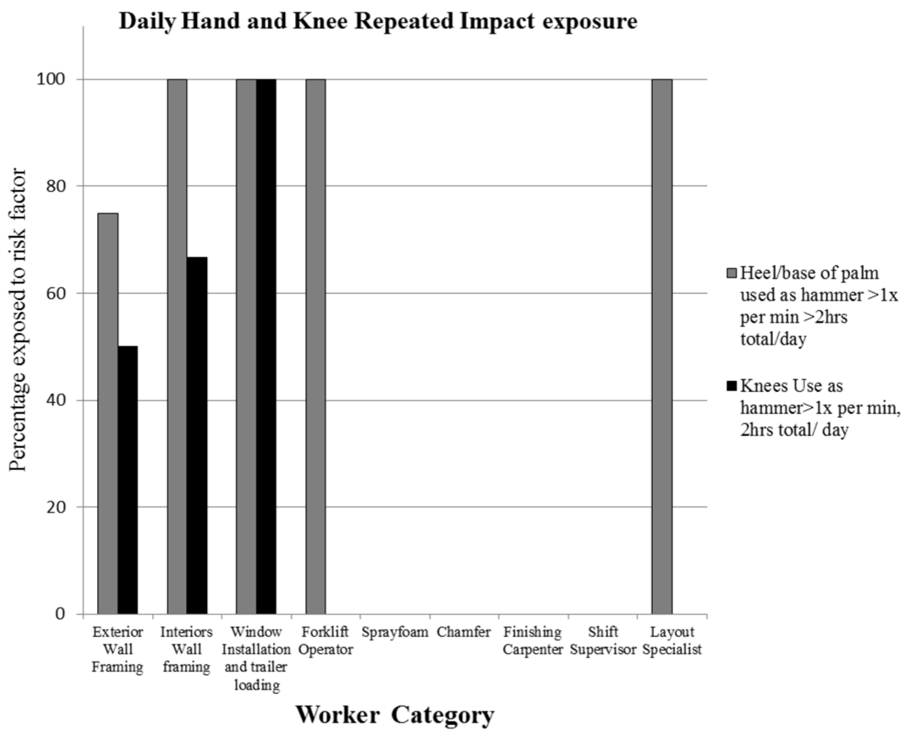


Figure 4.7: Percentage of workers indicating exposure to repetitive task

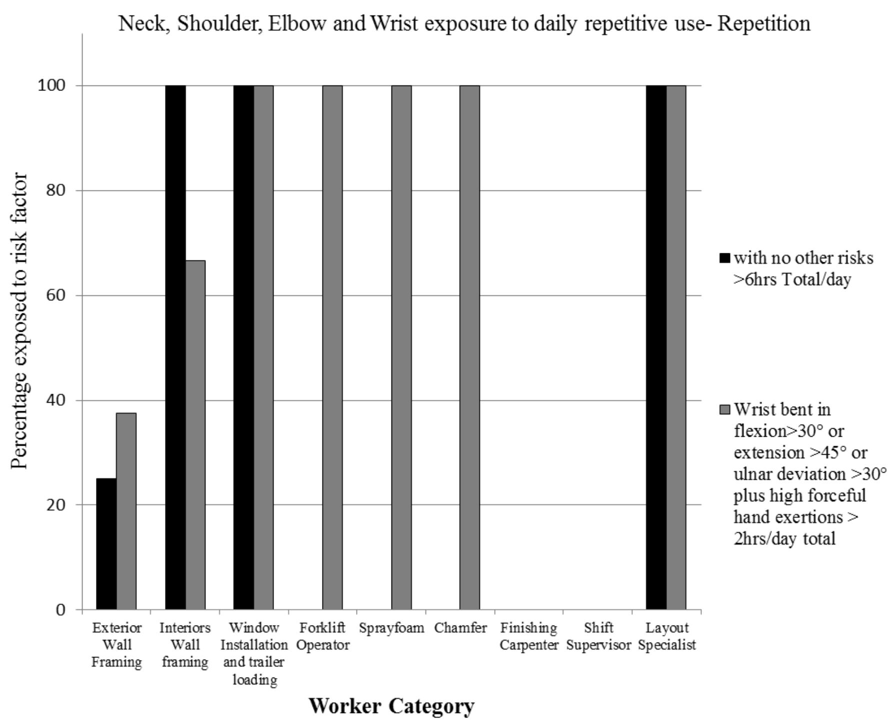


Figure 4.8: Percentage of workers indicating repeated impact on hands and knees

Discussion and Conclusion

- The results of the self-reported checklist (Figure 4.3 - Figure 4.8) shows that the task execution methods currently utilized by this construction plant expose the workers to a high potential for injury. A proactive, management-coordinated action will thus offer better potential for controlling or eliminating the risk of preventable WRMSDs in the company.
- Based on the lack of potential injury and injury symptom reports found, it can be concluded that worker reporting is not an effective means of ergonomic risk prevention; the legislation should be modified to recommend proactive assessment by management/employers.
- A comprehensive work task ergonomics analysis is thus proposed in order to verify the findings and identify areas where control and mitigation can be incorporated into job task planning.

4.2 Proposed Observation-Based Technique - ErgoCheck

Case 2: ErgoCheck-A new observation-based ergonomic analysis model.

13 hours of video data of the wall plating carpentry station (Figure 4.9) over a period of 6 weeks, (July 26th – August 31st, 2010, with an average of 4-hours observation per week), was collected and analyzed. This video data was collected over an extended period of time in order to ensure that the data was not biased and was a good representation of the normal process. This data served as the observation data for the case study application. The proposed ErgoCheck model was used to analyze and classify ergonomic risks from daily residential construction plating tasks. The results were also used to verify the conclusions from the checklist/survey in Section 4.1.1.

Study overview

The six ergonomic risk factors, (force, contact stress, environment, repetition, awkward posture, and organizational risk), were assessed based on the video observations. Significant body parts identified as being exposed to ergonomic risk were the hand/wrist, neck, legs, and upper-back. Significant observed postures included bending of neck > 30° (6.3 hours per day), back bending

> 30° (1.3 hours per day), and hand/wrist flexion (6.6 hours per day). Other risk factors included repeated activities and postures and hand force (gripping force). These were observed consistently and the data recorded and analyzed. The result of the ergonomic assessment has been applied to the REBA and RULA analysis methodology (Table 4.2), as well as the proposed ErgoCheck methodology (Table 4.3 and Table 4.4) for the purposes of validation.

Results, Validation and Discussion

Table 4.2 shows the resultant risk scores and classification based on the analysis of the subject of the case study using the REBA and RULA work analysis methods.

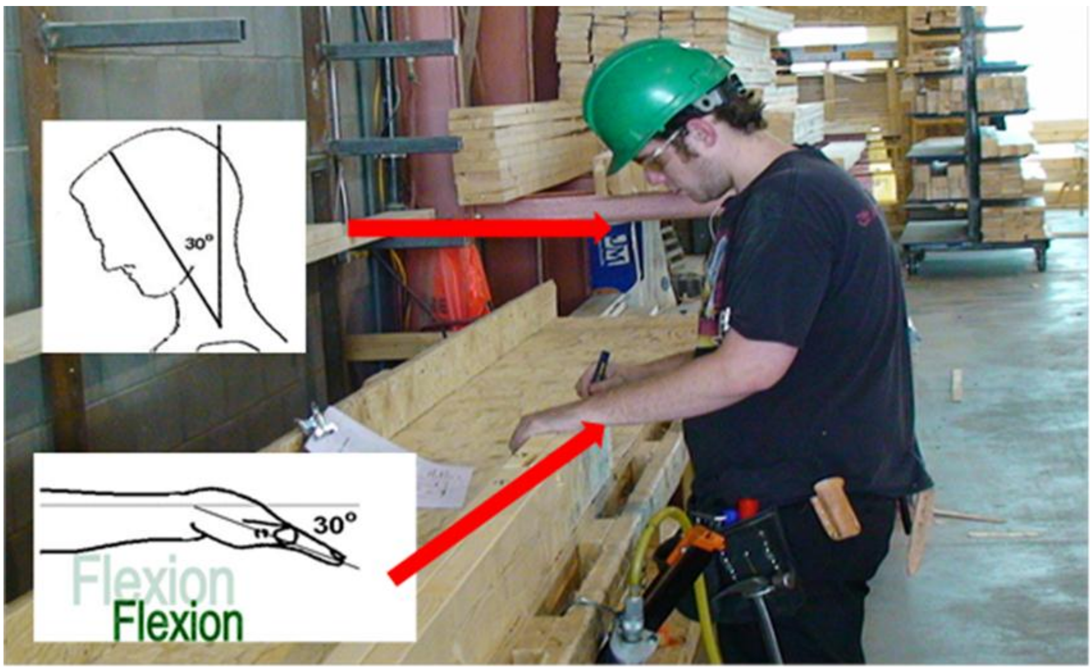


Figure 4.9: Exterior plating carpenter at work

The RULA and REBA analysis methods are mostly concerned with awkward work postures, with consideration of the effects of force/contact stress and coupling, but with no consideration of the effect of other risk factors such as hand-arm vibration (HAV), and the environmental and organizational conditions of the workplace. Both methods classify the risk as of medium risk severity/class. Table 4.3 shows the results of postural analysis based on the proposed methodology and presents the risk rating for each of the postures, both with organizational and duration factors considered and with them ignored. The results show that the risk related to upper-back posture is counteracted by total daily exposure and organizational factors, thus resulting in a change in the risk rating and classification from medium to low risk. Table 4.4 shows that repetition is the main risk for this worker, and that exposure to hand force is also an important risk factor for consideration. The resulting comparison shows that the medium risk classification as presented by all three methods is due to the medium hand/wrist exposure and partially to upper-back exposure. The activity should thus be modified to eliminate or reduce this risk.

Table 4.2: Ergonomic analysis results using REBA and RULA analysis methods

Method	Risk Score/Rating	Risk Classification	Contributing Risk Factors		
			Exposure Duration	Organizational Factor	Force
REBA	5	Medium		No	Yes
RULA	4	Medium	Yes	No	Yes

Table 4.3: Postural analysis results based on proposed methodology

Body Part	Without Considering Effect of Duration and Organizational Factor	Considering Effect of Duration and Organizational Factor
Upper Back	3 (Medium)	1 (Low)
Upper Arm	1 (Low)	1 (Low)
Lower Arm	1 (Low)	1 (Low)
Wrist/Hand	3 (Medium)	3 (Medium)
Neck	1 (Low)	1 (Low)
Legs	1 (Low)	1 (Low)

Table 4.4: Risk Summary

Body Part	Applicable Risk Factors					
	Without Duration and Organizational Factor			With Duration and Organizational Factor		
	Repetition	Environment	Force	Repetition	Environment	Force
Neck	Rr= 3, Medium	Rr=1, Low	N/A	Rr=9, Very High	Rr=3, Medium	N/A
Upper Back	Rr= 1, Low	Rr=1, Low	N/A	Rr=1, Low	Rr=1, Low	N/A
Hand/Wrist	Rr= 3, Medium	Rr=1, Low	Rr=1, Low	Rr=9, Very high	Rr=3, Medium	Rr=3, Medium
* (i) N/A (Not applicable), (ii) Rr (Risk rating) (iii) Very high, High, Low, Medium (Risk Classes)						

Based on the consistent ergonomic risk classification results and conclusion from all three methods as presented in Table 4.2 - Table 4.4, the proposed method is valid for use in that its results are consistent with existing models, while offering the opportunity for a more detailed analysis of risk causes and sources. The risks of exposure to HAV and contact stress are not significant and thus are not considered. Comparing the results of the proposed methodology with the exposure-response relationship (Figure 3.6), there is a high potential for the worker to develop Carpal Tunnel Syndrome (CTS), hand/wrist tendinitis, and tension neck. This is enforced by the presence of a combination of force and repetitive exposures and awkward postures for the neck and hand/wrist. This activity should thus be considered for modification in order to reduce/eliminate risk of these disorders.

Discussion and Conclusion

The proposed methodology has demonstrated an ability to correctly assess, quantify, and rate the daily ergonomic hazard exposures of residential construction work activities using the case study presented. It has introduced an avenue to account for the effect of exposure duration and work design on work-resultant exposure hazards. Furthermore, instead of resulting in an overall risk score, it scores risks for each body part separately, thus achieving greater clarity in determining the areas needing correction/changes and providing direction for preventive measures. It also shows capability of assessing the risk of HAV exposures, which has not been considered by other methods. The effect of psychosocial factors such as worker control over the work and issues related to mental stress resulting from work activities are also accounted for as organizational factors. Although personal factors such as worker relationships, volunteer or second jobs, home-related stress, and hobbies have not been accounted for by this methodology, anthropometry (sex, age, body weight, height) has been considered in determining ranges of safe exposure based on Occupational Health and Safety Administration (OSHA) guidelines for up to the 95th percentile of the worker population for Canada and the United States. It should also be qualified that the previous health histories of workers have not been accounted for in methodology. Still, overall this method gives a comprehensive assessment of the ergonomic risk to which each body part is exposed while executing daily construction work activities. It can be further extended to facilitate the prediction of potential WRMSDs related to the observed hazard exposure classes for each body part.

Case 3: A comparison of ErgoCheck model with REBA and QEC models.

Study Overview and Objective

There exist limited studies comparing risk assessment methods based on quantified demands and risk level/classification (Jones and Kumar 2007). Studies of QEC and REBA have demonstrated their ability to assess postural loading in the industrialized construction process (Kim et al. 2011; Rwamamara 2007; Jones and Kumar 2007). Jones and Kumar (2007) compared risk assessment output in a sawmill occupation by assessing the agreement between seven techniques, including REBA; the study showed significant disagreement between the methods. Also, Motamedzade et al. (2011) compared REBA with QEC and identified a significant correlation by observing 40 jobs in an oil company. Moreover, a number of observation-based techniques exist for work-related ergonomic risk assessments, but only limited agreement exists among them. This section evaluates ErgoCheck's sensitivity to ergonomic risk in construction workplaces by comparing its percentage agreement in risk classification with REBA and QEC. An exterior wall component plating carpenter and four window installation carpenters were observed for 15 days while fabricating wall panels. Daily construction tasks were documented for accurate ergonomic risk assessment by all three techniques. This study compares the risk classification of QEC and REBA techniques with ErgoCheck risk classification in order to determine their areas of agreement and disagreement in regards to identifying and classifying ergonomic risk based on work done by an exterior wall component plating carpenter (Figure 4.10a) and four window installation carpenters (Figure 4.10b) fabricating wooden wall panels for residential construction.

(a): Exterior wall component plating carpenter (b): window Installation carpentry crew

Figure 4.10: Observed carpentry activities

Methodology

Work description and data Collection

This study was conducted with the goal of investigating the correlation between the risk assessment results of ErgoCheck and those of REBA and QEC in a residential construction factory in which two jobs were studied.

A total of 130 hours of video observations of all four members of the window installation crew and one exterior wall component plating carpenter over a total period of 4 weeks was analyzed for this study. The exterior wall component plating carpentry task involved measuring, marking, and cutting pieces of lumber for use by the exterior wall component and exterior wall assembly carpenters for fabricating exterior wall panels. The identified risk factors included bending of the neck and back greater than 30°, hand/wrist flexion, as well as frequent movement. The window installation crew performs two basic functions: (i) Openings for windows are cut out on the completed wall panels and the windows are fixed within the openings. Crew members are also involved in ensuring windows are air tight. (ii) After the wall panels are completed, the window crew assists in the process of lifting the panels from the work station to the spraying station or into the delivery truck with the help of an overhead crane system. Identified risk factors include bending of the neck and back, squatting, kneeling, raising hands above the shoulder, and hand force. A typical work day for both carpentry crews is a 7:00am-4:30am shift, which includes two unpaid 15-minute coffee breaks and one paid 30-minute break. Workers' ages ranged from 20 to 55 years (and with an average height of 182 cm) (Table 4.1). Additional task information required for complete assessment by the ergonomic risk assessment techniques (REBA, QEC, and ErgoCheck) was documented. Since the author's focus was to compare the outputs of the observation-based methods, REBA and QEC, to ErgoCheck, other potential ergonomic techniques such as ERGOBUILD and Ovako Work Posture Analysis System (OWAS) were not assessed as part of the study.

Analysis

The REBA method (Hignett and McAtamney 2000) assesses the risks posed by static and repeated work postures on the upper extremities, legs, and muscles, and assigns a final risk score, risk classification, and recommendation (1 = negligible risk; 2 or 3 = low risk, change may be needed; 4 to 7 = medium risk, further investigation, change soon; 8 to 10 = high risk, investigate and implement change; 11+ = very high risk, implement change). The QEC developed by Li and Buckle in 1998 and later enhanced by David et al. in 2003 is an ergonomic assessment technique which groups the body into four regions: back, shoulders/arms, neck, and hands/wrists. The observed group is rated with two to three step scales using fuzzy logic. This method identifies risks arising from task weights, durations of tasks, hand force required, visual demands, driving force, use of vibrating tools, work pace, and stress. It produces both individual risk scores and classifications for each body part. It also determines an overall risk score by adding scores from all the body groups and dividing the sum by the maximum score (176 for manual material handling tasks and 162 for others). Satisfactory exposure is assigned for scores <40% of maximum, 41%-50% (further investigation, changes recommended), 51%-70% (high risk), above 70% (very high risk, requiring immediate intervention). These correspond to four risk levels: 1-4—low, moderate, high, and very high. As presented in Section 4.2.1, ErgoCheck assesses the exposure of each body part (back, neck, shoulder, hand/risk, arm, shoulder, and leg) to any identified ergonomic risk factor. It calculates a final risk score by multiplying the risk score from each factor with an organizational factor and a duration factor (Equation 3.1-Equation 3.9). The final risk scores are categorized as 0-6 (low risk), 6-13 (medium risk), 12-15 (high risk) or >15 (very high risk). This process is repeated for each body part (Section 3.2.1). The method also incorporates the effect of psychosocial factors and anthropometry, and is specifically designed for construction-related work analysis.

The following re-classification of risk was developed to compare the methods: (i) Individual Assessment: The general risk classification by REBA was applied to all the body parts under study in order to compare the results to those of QEC and ErgoCheck, which both provide a risk class for each body part. (ii) General Risk Class: The highest possible risk class was assigned as a general risk class for the ErgoCheck technique in order to accommodate the general risk assignment utilized in QEC and REBA. Note that ErgoCheck combines all the risk factor classifications and assigns the maximum risk class as a summary for each body part.

Basis of Comparison (Measures of agreement in Risk Classification with ErgoCheck)

Only limited statistical techniques could be used for assessing agreement between the methods, as only four risk classes were produced by each method. The results from each applied method were compared to those of ErgoCheck based on (i) General risk classification, (ii) body part risk classification, (iii) percent agreement (Araujo and Born 1985) of risk classification for each body part for "Perfect risk class match" and "at risk", and (iv) Spearman's rank correlation coefficient of each body part risk classification.

Results

The ergonomic risk assessment outputs are presented for ErgoCheck, REBA, and QEC techniques. Table 4.5-Table 4.7 show the REBA risk classification process. The result shows a final risk score of 5 (medium risk) for the exterior wall component plating carpenter and 9 (high risk) for the window installation carpenters.

Table 4.5: REBA Neck, Trunk and Leg Analysis

Worker Category	Neck, Trunk and Leg Analysis						
	Neck	Trunk	Leg	Body Segment Risk Score	Muscle Use	Force/ Load	Neck, Leg and Trunk Score
Exterior Wall Plating Carpenter	2	3	1	4	NA	0	4
Window Installation Carpenters	2	4	3	7	NA	0	7

Table 4.6: REBA Arm and Wrist Analysis

Worker Category	Arm and Wrist Analysis							
	Upper-arm	Lower-arm	Wrist	Wrist Twist	Body Segment Risk Score	Muscle Use	Force/ Load	Coupling	Arm/Wrist Score
Exterior Wall Plating Carpenter	1	1	3	0	2	NA	NA	0	2
Window Installation Carpenters	3	1	2	0	4			0	4

Table 4.7: REBA Risk Classification and Summary

Worker Category	Risk Assessment	Task Total Risk Score	Activity Score	Final Task Risk Score	Risk Class	Remarks
Exterior Wall Plating Carpenter	REBA	4	1	5	Medium risk	Further investigation, change soon
Window Installation Carpenters	REBA	8	1	9	High risk	Investigate and implement change

The QEC assessment resulted in the following risk scoring for the exterior wall component plating carpenter: A2, B3, C1, D1, E1, F1, G3, H1, J3, K1, L1; and A3, B3, C1, D1, E1, F1, G2, H1, J3, K2, L1 for the window installation carpenters. Table 4.8 and Table 4.9 show that for both work tasks, QEC classifies the back, shoulder/arm, and hand/wrist as "moderate risk." The neck was classified as "very high risk" for the exterior wall component plating carpenter and "high risk" for the window installation carpenters. The summary risk scores were 53% and 58%, respectively, signifying a "high risk" for both cases.

Table 4.8: QEC Risk Assessment for Exterior Wall Component Plating Carpenter

Body Part	Risk Scores							Risk Class
	Score 1	Score 2	Score 3	Score 4	Score 5	Score 6	Total	
Back	4	8	6	NA	2	6	26	**Moderate**
Shoulder/Arm	2	6	6	2	6	NA	22	**Moderate**
Wrist/Hand	2	6	6	2	6		22	**Moderate**
Neck	10	6	NA	NA	NA	NA	16	**Very High**
				Total Score for all Body parts			86	
				Maximum Score			162	
				Summary Score			53.1%	**High Risk**

Table 4.9: QEC Risk Assessment for Window Installation Carpenters

Body Part	**Risk Scores**							**Risk Class**
	Score 1	**Score 2**	**Score 3**	**Score 4**	**Score 5**	**Score 6**	**Total**	
Back	6	10	6		2	6	30	**Moderate**
Shoulder/Arm	2	6	6	2	6	NA	22	**Moderate**
Wrist/Hand	4	6	8	4	6		28	**Moderate**
Neck	8	6	NA	NA	NA	NA	14	**High**
				Total Score for all Body parts			94	
				Maximum Score			162	
				Summary Score			58.0%	**High Risk**

The ErgoCheck assessment results in a medium risk classification for the upper-back and hand/wrist, low risk classification for the legs and lower-/upper-arm and high risk classification for the neck for the exterior wall component plating carpenter. This leads to a summary classification of "high risk" for this task (Table 4.10). The window installation task is assigned "medium risk" for the legs, upper-back, hand/wrists and shoulder/arm and low risk to the neck, resulting in medium overall risk.

Table 4.11 shows the ergonomic risk assessment results of the window installation carpenters. Table 4.12 presents the general risk summary for both worker categories. Table 4.13 and Table 4.14 show the percentage agreement comparison results for a "perfect risk class match" for the exterior wall component plating and window installation tasks, respectively. This assessment is based on a perfect match in the risk classification of each body part by the QEC and REBA techniques when compared with ErgoCheck classification. All three techniques show perfect agreement when assessing the upper-back and hands/wrist. This does not apply to the neck and shoulder/arm assessment, however. Spearman's rank correlation results in r = 0.85 for comparison of ErgoCheck with QEC, and r = 0.55 when compared with REBA (mean % agreement between ErgoCheck and QEC for all body parts = 81.25% and with REBA = 79.25%). For the exterior wall component plating carpenter, there is perfect agreement between ErgoCheck and QEC assessments for all the body parts except for the neck, which records only 33% agreement. This results in a very poor value of r = -0.2 when comparing ErgoCheck with QEC. However, there is a better correlation result, r = 0.7, when comparing ErgoCheck with QEC and REBA, respectively (mean % agreement between ErgoCheck and QEC for all body parts = 83.25% and with REBA = 58.5%).

Table 4.10: ErgoCheck Risk Assessment for Exterior Wall Component Plating Carpenter

Risk Factors	Exterior Wall Plating Carpenter						
	Body Part	Upper-back	Neck	Legs	Hand/Wrist	Lower-arm	Upper-arm
Awkward Posture	Rs	3	2	1	6	1	1
	Mo	0.5	1.5	0.5	0.5	0.5	0.5
	Md	2	3	2	3	3	3
	Rhs	3	9	1	9	1.5	1.5
	Rr	1	3	1	3	1	1
	Risk Class	Low	Medium	Low	Medium	Low	Low
Repetition	Rs	6	3	3	6	3	3
	Mo	0.5	1.5	0.5	0.5	0.5	0.5
	Md	2	3	3	3	3	3
	Rhs	6	13.5	4.5	9	4.5	4.5
	Rr	3	6	1	3	1	1
	Risk Class	Medium	High	Low	Medium	Low	Low
Risk Summary		Medium	High	Low	Medium	Low	Low
Overall Risk Class		**High Risk**					

Table 4.11: ErgoCheck Risk Assessment for Window Installation Carpenters

Risk Factors	Window Installation Carpenters					
	Body Part	Upper-back	Neck	Legs	Hand/ Wrist	Shoulder
Awkward Posture	Rs	3	2	4	3	4
	Mo	0.5	0.5	0.5	0.5	0.5
	Md	3	1.5	3	2	2
	Rhs	4.5	1.5	6	3	4
	Rr	1	1	3	1	1
	Risk Class	Low	Low	Medium	Low	Low
Repetition	Rs	6	6	6	6	6
	Mo	0.5	0.5	1	0.5	0.5
	Md	3	1.5	2	2	2
	Rhs	9	4.5	12	6	6
	Rr	3	1	3	3	3
	Risk Class	Medium	Low	Medium	Medium	Medium
Risk Summary		Medium	Low	Medium	Medium	Medium
Overall Risk Class		**Medium Risk**				

Table 4.12: Summary of risk Classification

Technique	Task	
	Exterior Wall Plating Carpenter	Window Installation Carpenters
ErgoCheck	High Risk	Medium Risk
QEC	High Risk	High Risk
REBA	Medium Risk	High Risk

For the “at risk” assessment (Table 4.15 and

Table 4.16), the risk classes are grouped into new levels: Level 1 - “no risk and low risk”; level 2 - “medium and high risk"; and level 3 - “very high risk.” Based on this new risk class grouping, percentage agreement is calculated similar to that for Table 4.13 and

Table 4.14. The “at risk” method shows an overall good correlation for both tasks when both techniques are compared with ErgoCheck. This is expected as a result of the class grouping. The Spearman’s rank correlation results in r = 0.6 and r = 0.7, respectively, when compared with

QEC and REBA for the exterior wall component plating carpenter and r = 0.7 for comparison of ErgoCheck with QEC and REBA for the window installation carpenters. The mean % agreement = 79.25% and 87.5% for comparison of ErgoCheck with QEC and REBA, respectively, for the exterior wall component plating carpenter and 87.5% mean agreement with both techniques for the window installation carpenters.

Figure 4.11 and Figure 4.12 are scatter plots showing the matching of ergonomic risk classifications for all ErgoCheck, QEC, and REBA for both work categories for the “perfect risk class match” case. These figures demonstrate the poor agreement of REBA and QEC with regards to assessing neck risk exposure. Poor overall agreement can also be observed between the REBA classification and the QEC and ErgoCheck classifications when considering the window installation task.

Table 4.13: Percentage agreement comparison “Perfect risk class match” for exterior wall component plating task

Technique % Agreement	Upper-back	Shoulder/Arm	Hand/ Wrist	Neck
ErgoCheck Vs QEC	100%	50%	100%	75%
ErgoCheck Vs REBA	100%	50%	100%	67%
QEC Vs REBA	100%	100%	100%	50%

Table 4.14: Percentage agreement comparison “Perfect risk class match” for window installation task.

Technique % Agreement	Upper-back	Shoulder/Arm	Hand/ Wrist	Neck
ErgoCheck Vs QEC	100%	100%	100%	33%
ErgoCheck Vs REBA	67%	67%	67%	33%
QEC Vs REBA	67%	67%	67%	100%

Table 4.15: Percentage agreement comparison “At Risk” for exterior wall component plating task

Technique % Agreement	Upper-back	Shoulder/Arm	Hand/ Wrist	Neck
ErgoCheck Vs QEC	100%	50%	100%	67%
ErgoCheck Vs REBA	100%	50%	100%	100%
QEC Vs REBA	100%	100%	100%	67%

Table 4.16: Percentage agreement comparison “At Risk” for window installation task

Technique % Agreement	Upper-back	Shoulder/Arm	Hand/ Wrist	Neck
ErgoCheck Vs QEC	100%	100%	100%	50%
ErgoCheck Vs REBA	100%	100%	100%	50%
QEC Vs REBA	100%	100%	100%	100%

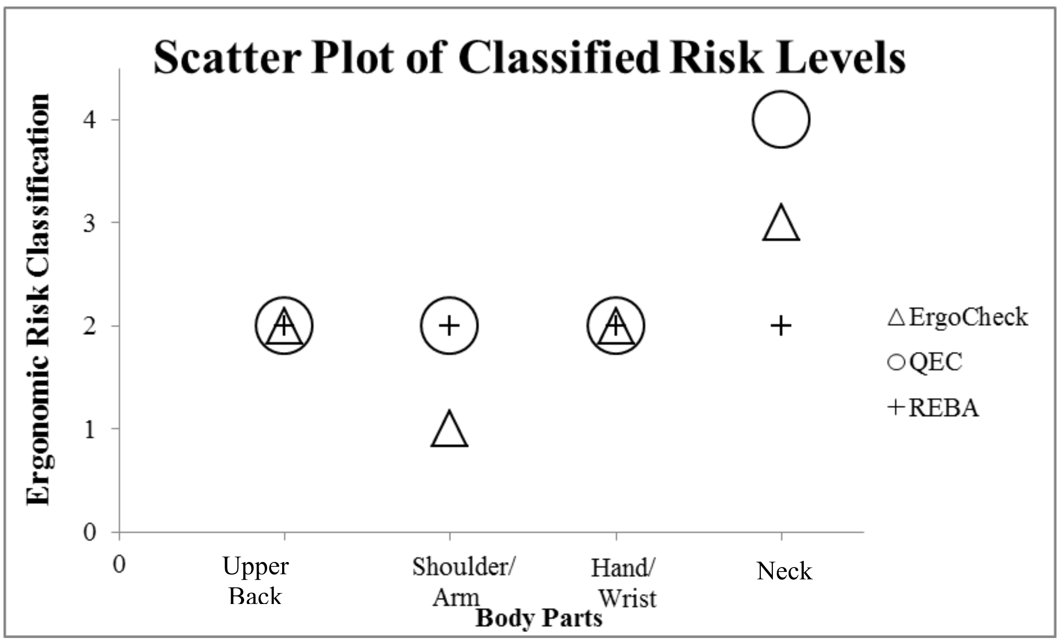


Figure 4.11: Ergonomic risk classifications of exterior wall component plating task

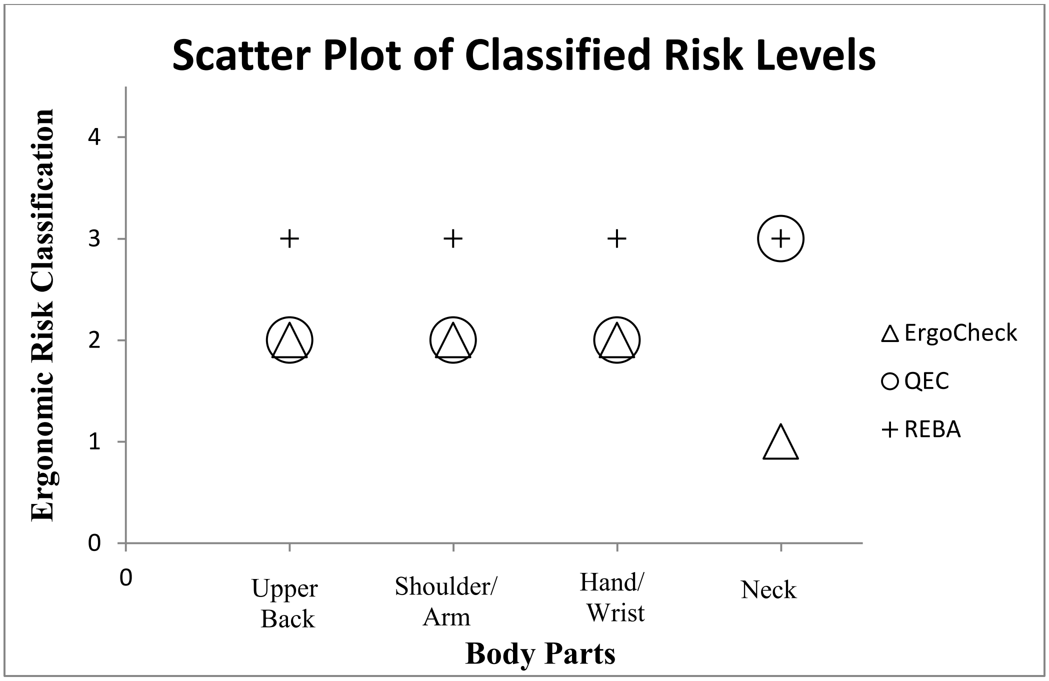


Figure 4.12: Ergonomic risk classifications of window installation task

Discussion

The key finding of this study are the agreement of moderate to high risk class by all three observation-based techniques for all the body parts except the neck. Comparisons between ErgoCheck and QEC show an overall strong correlation in risk classification for most body parts; this correlation is important as both techniques carry out body part-based assessments and risk classifications. There is a poor correlation in the classification of risks, especially for neck-related risk exposures. This may be related to the fact that all three methods employ a hypothetical risk weighting/scoring system; it may also be attributable to the fact that ErgoCheck recognizes the impact of the organizational factor and actual duration of exposure, while QEC only assesses the total task duration and repetition and REBA does not emphasize either the duration or the worker's control over the task. This highlights a major advantage of ErgoCheck, as the impact of these two factors could increase or reduce the risk significantly.

The low negative Spearman's rank coefficient (r = -2) between ErgoCheck and QEC for the window installation carpenter during the perfect match assessment is due to the wide disagreement in the risk classification for the neck region.

The consistently average correlation of the ErgoCheck assessment with the REBA technique may be caused by the REBA reclassification. REBA's main weakness is that its assessment is not body part-based, resulting in the assignment of a general risk class for the whole task without showing a detailed breakdown of the individual actions.

This study established that ErgoCheck is capable of and sufficiently sensitive to identify and correctly classify ergonomic risk in residential construction tasks performed in an industrialized setting. This shows that ErgoCheck can replace the observation-based methods of risk assessment. The results support the hypothesis that there is strong and consistent correlation between REBA and QEC (Motamedzade et al. 2011).

An important limitation of the present study has been that only two work tasks were selected for assessment. Furthermore, comparison of ergonomic risk classification was limited to only two observation-based methods, REBA and QEC; other potential methods were not assessed.

Conclusion

The study demonstrates a significant agreement between ErgoCheck, QEC, and REBA in evaluating and classifying work-related risks. The differences between the methods show the insensitivity of each method caused by the differing weighting of the risk factors. These discrepancies present important areas to consider when using these three techniques to analyze construction work tasks. The agreement demonstrated by REBA and QEC techniques when compared with the ErgoCheck assessment validates ErgoCheck as a reliable ergonomic assessment technique, shows the extra sensitivity of ErgoCheck compared to the other methods, and confirms the value of its application for the assessment of factory-based construction tasks.

4.3 Computer methods – Applications of Biomechanical Analysis and Discrete Event Simulation

Two computer-based techniques are applied to assess the ergonomic hazard from daily floor framing activities. The proposed model (ErgoBioMCheck) developed in Section 3.2.3 is applied in ***Case 4*** to quantify the biomechanical loads (forces and moments) on the lower-back and to assess the risk of lower-back pain (LBP) due to cumulative exposure to compression and shear loads over time. Also, the discrete event simulation (DES) application (ErgoSymulate) process described in Section 3.2.4 is applied to a second case study (***Case 5***) to assess the potential application of DES in ergonomic risk analysis of occupational tasks. This analysis assesses daily awkward work postures of the neck, hand, and back segments. Both case studies are cited in the floor framing line of the Landmark facility in Edmonton.

Case 4 assesses the ergonomic risks resulting from biomechanical loads on the lower-back based on the manual floor panel production line. This study is based on data from video recordings of the floor framing process captured between July 26 and August 31, 2010. The proposed ErgoBioMCheck model was applied to assess the risk. The results and recommendations of this study show the areas of highest ergonomic risk from the framing task and inform decisions for controlling excessive exposure. Case 5 applies the DES model process proposed as ErgoSymulate in order to analyze the postural risk resulting from the same floor framing task after the initial changes. This study is based on video data captured in August, 2011 in the new Landmark factory.

Although Cases 4 and 5 assess the same task, there have been several changes to the floor framing process implemented by the company in an effort to improve safety and increase productivity. However, the tasks remain the same.

Case 4: Biomechanical assessment of lower-back compression and shear stress from floor framing residential construction tasks.

Objective

This case study assesses the risk of manual floor panel framing tasks in a residential construction plant by applying the developed ErgoBioMCheck model to assess the potential instantaneous and cumulative lower-back compression and shear forces and moments during the execution of the described framing activities.

Task Description

Manual floor framing is a physically demanding task which involves dynamic motions and loading scenarios. Most tasks are performed in awkward postures due to the design of the working area (station design) and height of the working platform. The manual floor framing task involves significant lifting, lowering, nailing, and cutting tasks and is carried out on the pin table by two (2) framing carpenters (Figure 4.13). The reach and nature of the task require one or both carpenters to climb onto the pin table in order to work. This exposes them to increased risk from awkward bending (neck, back) and squatting postures.

Floor Framing Process: After receiving the work order, the carpenters check the drawings to determine the floor type to be framed in that day. Both workers walk to the component storage area where they reach to select (Figure 4.14) and carry (Figure 4.15) the appropriate components for the floor design back to the pin table. The components include various dimensions of lumber (joists, rim-boards, and blocking). Usually, in cases where the total weights of the components exceed about 70 pounds, both workers are involved in the carrying activity. This cycle continues until all required components have been brought to the pin table. Once this activity has been completed, the carpenters climb onto the table to assemble the components according to the given specifications. The components are then nailed to form the outer frame of the floor. One worker (Worker 2) then climbs down from the pin table while the other (Worker 1) remains on the table. Both workers then proceed to nail the components according to the design specifications (Figure 4.16). Depending on the surface to be nailed, the carpenter may nail while squatting on the table or standing on the ground. Usually one carpenter (Worker 1) stays on the table while the other (Worker 1) nails from the ground, (except when the activity requires that both be working from the same surface). Once nailing is completed, an adhesive is applied to the top of the joists and rim-boards. The carpenter on the floor (Worker 2) then walks to the sheathing storage pile and manually bends (Figure 4.17) to lift the sheathing board, carries it to the work station, and lowers it in place on top of the framed components. Both workers align the sheathing on top of the components and secure them in place by nailing (Figure 4.18) according to the layout. After nailing a given sheathing board, the carpenter on the floor returns to bring in another sheathing panel. This cycle continues in the same sequence until all sections are covered and nailed. The floor panel is then moved to the next station where holes are cut for attachment of craning straps. Cutting activities are usually required as part of this framing task. Figure 4.13 - Figure 4.18 are 3D visualization models developed to represent the described process and work area using two different 3D modelling softwares (3D Studio Max and Siemens Tecnomatix Jack).

In actual cases, the daily framing tasks involve the framing of different floor panel models; however, for simplicity, the framing process of only one floor model (Model 11_150) is assessed for a continuous 8-hour work shift. This model, shown in Figure 4.16 and Figure 4.18, is made up of 18 sections with dimensions of 36ft x 14ft x 15in (Figure 4.18).

Figure 4.13: Manual Floor Framing Process

Figure 4.14: Worker reaching to pick component at storage

Figure 4.15: Worker carrying component

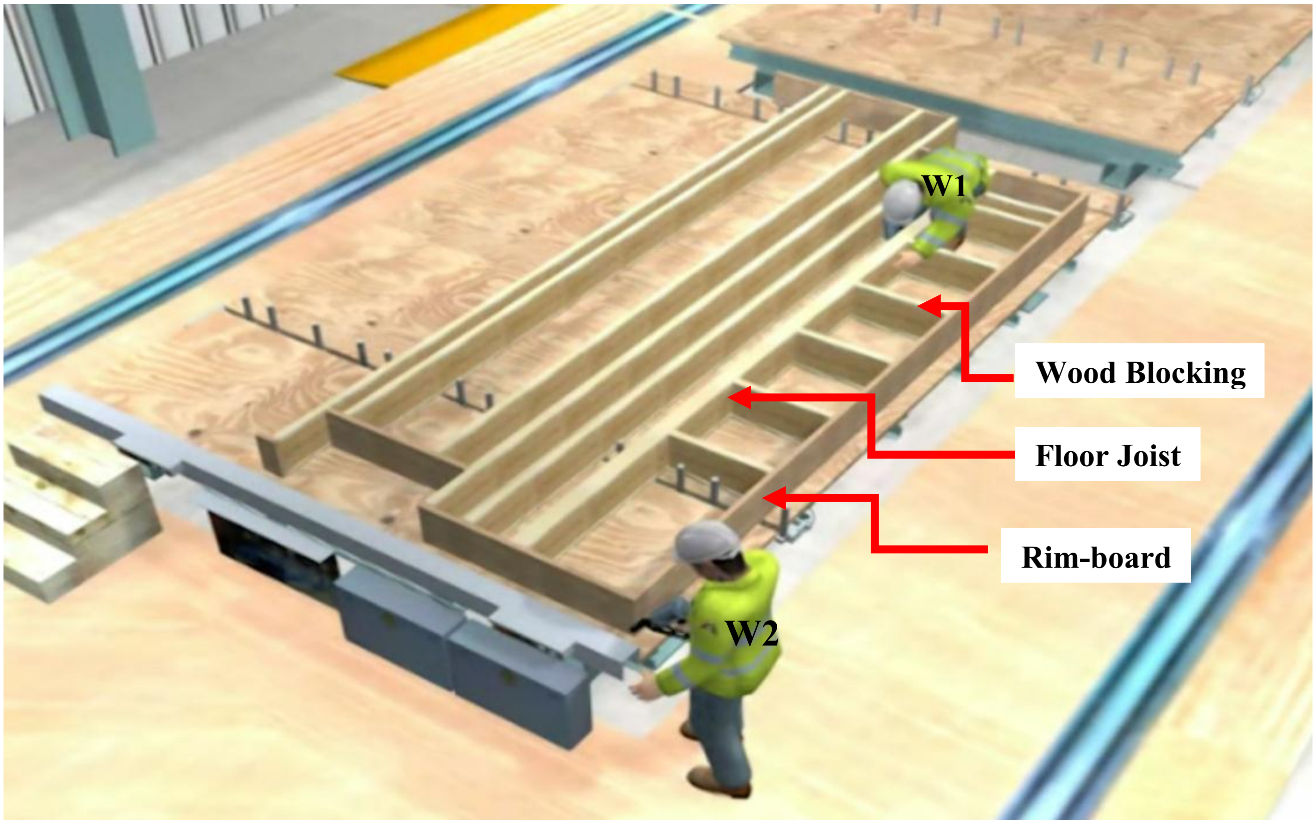


Figure 4.16: Floor framing (nailing of rim-board, joists, and blocking in awkward postures)

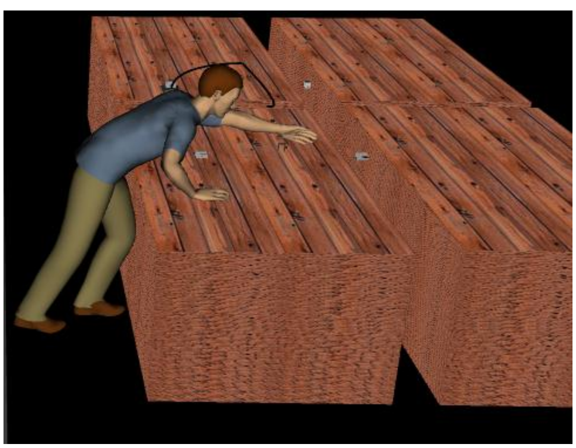


Figure 4.17: Worker 2 bending to lift sheathing board

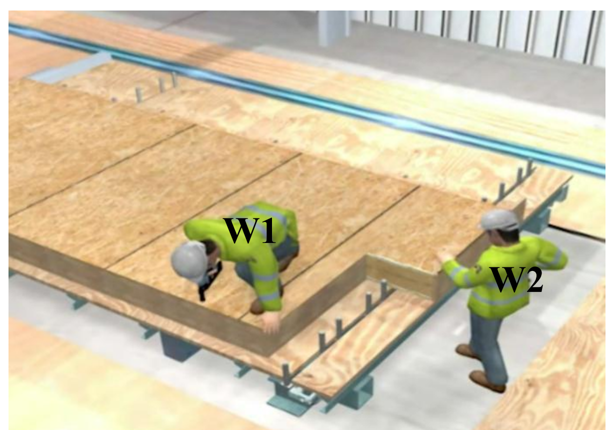


Figure 4.18: Floor framing (nailing of sheathing boards in awkward postures)

Scope of Study

Activities to be assessed: Ergonomics studies and interventions are usually designed based on the tasks or activities which are seen as being the most stressful or hazardous. Based on the task description, three main activity groups have been identified as posing the greatest risk of ergonomic injury to the workers and are selected for assessment due to the length of time, force/muscle load, and awkward posture. These include: (a) carrying activities, (b) nailing activities, (c) other activities.

(a) Carrying Activities: These activities involve the following sub-activities

1) Transporting Components (rim-boards or joists) from storage to the workstation. This involves the following:
   - Walking to the load area (component storage) without load (body weight)
   - Reaching to touch the component
   - Lifting the component from the stack
   - Walking back (returning) to the work area with the load (components)
   - Lowering the load onto the work table

   Carrying may be accomplished by each worker individually (up to about 65 pounds) or by both workers carrying heavier loads (greater than 65 pounds).

2) Transporting sheathing from storage (stack) on the floor to the workstation (lifting and carrying heavy load) by Worker 2.
   - Walking to the load area (sheathing stack/pile storage) without load (body weight)
   - Bending to touch sheathing board (awkward posture)
   - Lifting sheathing board to an upright posture
   - Walking back (returning) to the work area carrying load (sheathing)
   - Lowering the load onto the work table

(b) Nailing activities

- Nailing of rim-board and joists or sheathing in awkward squatting posture on the table by worker.
- Nailing of rim-board and joists in awkward bending posture by the second carpenter (worker 2) (with neck bent).

Nailing activities are assessed only based on the posture adopted during the nailing activity, the weight of the nailing gun, and the duration of the nailing activity.

(c) Other Activities

Other activities include tasks which are not included in the main tasks and for which posture or loading condition is not hazardous. These include activities such as climbing the table (up/down); cutting sheathing; installing crane straps; cutting/routing for strap installation; measuring, marking, and cutting sheathing; and checking drawing activities. Body weight, forces, and torques due to the segment centre of mass are the prevalent factors in these cases. It may be necessary to account for these scenarios in order to achieve a cumulative load assessment. However, only the nailing and free-standing postures will be assessed under this category. Also, for these activities, two considerations will be made: (i) only the activity duration will be used in computation; and (ii) external loads will be assumed to be zero (no external loads) except for the nail gun weight.

Basis and type of assessments to be performed: The types and bases of assessments to be executed are as follows:

- Ergonomic analysis will be based on an application of the proposed dynamic biomechanical models (ErgoBioMCheck).
- Instantaneous and cumulative dynamic forces, torques, and moments due to body segments and external loads generated around the shoulder and lower-back will be estimated.
- A biomechanical assessment of forces, torques, and moments of body segments is limited to the head/neck, upper-arms, lower-arms, and upper-back postures.
- Muscle strength statistics from the research (mostly based on Mital and Kumar 1998a,b) for select population and age class are incorporated for the assessment of fatigue and productivity.

The results provide a basis for recommending administrative and engineering controls for reduction of the identified ergonomic hazards.

Methodology

The methodology of this study involves the following: study set-up, assumptions, data source, physical demand analysis, and ergonomic analysis.

(1) Study Setup

The following tasks are identified based on the project description and video recordings.

Table 4.17: Activities, distance and durations

#	Activity	Distance travelled (m)	Duration (min)
1	Check Drawing		2
2	Bring in Components	6	3 per trip
3	Align Components on Table		10
4	Nail Rim-board		Per section
5	Apply Adhesive on Rim-board and joists		2
6	Align Sheathing on Frame		0.2
7	Nail Sheathing		Per section
8	Measure, mark, cut and drill for craning		0.5
9	Cut Sheathing Waste		0.5
10	Attach Strap		0.5
11	Clean Up		0.7
12	Reach for component		2/60
13	Lift Component		3/60
14	Lift Sheathing		4/60
15	Lower Sheathing		3/60
16	Nail Sheathing	per section	5/60

The floor framing components and equipment dimensions are presented in Table 4.18.

Table 4.18: Floor Framing Station, Components and equipment dimensions

Group	Item	Dimensions			Unit Weight	Total Weight	Quantity
		Length (ft)	Width (in)	Depth (in)	lbs/ft	(lbs)	
Rim-boards (14" X 1 ¼" TimberStrand Laminated Strand Lumber (LSL)	Item 1	12	1.5	14	5.1	61.2	
	Item 2	7.1	1.5	14	5.1	36.2	
	Item 3	32.5	1.5	14	5.1	134.4	
	Item 4	7.1	1.5	14	5.1	36.2	
	Item 5	6	1.5	14	5.1	30.6	
Joists (14" X 2 5/16" TJI 230 Joists)	Item 1	2.8	2 5/16	14	3.3	9.24	7
	Item 2	32.5	2 5/16	14	3.3	77.95	4
	Item 3	36	2 5/16	14	3.3	87.8	2
4' x 8' OSB Sheathing		8	48	0.5		52.8	14
Nailing Gun	Paslode					13.8	
Router						8	
Pin Table		40	240	28.7		NA	1

(2) Assumptions

a. Adopted postures are assumed to be consistent for the same activity for all cycles.

b. Average values of recommended maximum forces for each task are based on Mital and Kumar (1998a,b) and are presented for each muscle based on Table 4.24.

c. Activities are assessed based on work being performed in a 90° sagittal plane (Figure 2.13)

d. Both workers are assumed to be right-handed.

e. Components weighing more than 65 pounds are lifted by both workers. Thus the weight borne by each worker is half the total weight of the component. Both workers are assumed to adopt the same posture when lifting together.

f. The case study example is somewhat simplistic. Inertia terms have not been included in the force calculations.

g. A dynamic kinematics-driven approach satisfying kinematics and dynamic equilibrium conditions has been employed to account for muscle forces under given postures and loads.

h. Net moments, muscle forces, and compression and shear forces have been estimated using biomechanical model equations developed for each respective lifting scenario.

i. Since the lifting and lowering phases of the study were relatively slow (greater than 2 seconds), the effect of inertia has not been deemed important (Bazrgari et al. 2007) and has thus been omitted from the estimations of compressive and shear forces. Also, the influence from Coriolis acceleration has been omitted.

j. For lowering tasks, the acceleration components of the load and body segments are deducted from the equation (a_y = -ve).

k. The erector spinae muscles are assumed to be the sole contributors in resisting the moment at the L5-S1 joint, and they are assumed to act at a perpendicular moment arm of 5.0 cm to the L5/S1 interface.

(3) Data Sources

- For validation purposes, for each activity, the most common recorded work postures (body segment angles) adopted during each activity have been modeled in the 3D Tecnomatix Jack model. The segment angle displayed by the model has then been recorded as the observed postural angle.

- Strength Data: For consistency, all strength data has been based on Kumar (1998a,b).
- Anthropometric data: These data has been measured for each worker.
- Table 4.20 shows the centre of mass locations for each segment. The lower-arm (including the hand) segment is referenced to the wrist axis; the upper-arm is referenced to the elbow axis; the head and neck is referenced to the vertex (top of head) and the upper-body is referenced to the shoulder axis (refer to Table 2.5 and Figure 2.17).
- Table 4.21 shows the average segment mass for Worker 1 and Worker 2. These are estimated based on an average of the results from Table 2.6 and Table 2.7.
- Weight of OSB sheathing = 79N/m^2. Items such as crane straps, shop drawings are of negligible weight.

Table 4.19: Worker anthropometric data

Worker Name	Age	Stature (Height) cm	Gender	Abdominal Depth (cm)	Upper Arm Length (cm)	Lower Arm + hand length (cm)	Head/Neck Height (cm)	Upper-back Length (cm)	Weight (kg)
Worker 1	38	172.5	Male	18.9	30.7	46.3	22.4	36.8	77.7
Worker 2	29	186.2	Male	20.4	33.16	50.04	24.2	39.8	87.4

Table 4.20: Centre of Mass (COM) locations for each segment from reference axis for framing carpenters from anthropometric data

Worker Name	Upper-arm COM (r'_{UA})	Lower-arm+ hand COM (r'_{LA})	Head/Neck (COM) (r'_{HN})	Upper-back COM (r'_{UB})
Worker 1	17.32	14.91	9.7	18.84
Worker 2	18.71	16.1	10.48	20.35

Table 4.21: Workers anthropometric data –Average Segment mass (Kg)

Worker Name	Upper Arms (kg)	Lower-arms + hand (kg)	Head/Neck (kg)	Upper-back (kg)	Total Weight (kg)
Worker 1	4.38	3.75	6.24	37.04	77.7
Worker 2	4.92	4.22	6.91	41.95	87.4

(4) Physical Demand Analysis

The components to be lifted include: (i) rim-boards; (ii) joists; (iii) blocking; and (iv) sheathing boards. Other considerations include: (i) height of pin table from the floor; and (ii) total working height during nailing of sheathing (Pin table + component height).

Based on the task demand and the weight of the component, Table 4.22 shows the allocation of carrying activities (load mass) and also the estimated segment masses for each worker. For heavy lifts requiring two-person lifts, the total mass has been divided into two, such that the analysis assumes that each worker is lifting only half the weight of the component. For nailing activities, the weight of the nail gun is accounted for as an external load (13.8 pounds). Table 4.23 shows the postural angles for each segment as adopted by the workers while executing the tasks. The angle recorded for each activity is the final angle adopted at the termination of the activity. The initial angle is the final angle of the preceding activity. Table 4.24 shows the peak dynamic lift strength estimates for populations with similar characteristics to those of Workers 1 and 2. These have been adjusted for age, sex, and reach factors, respectively. The estimated values represent recommended safe dynamic lifting limits based on the case study variables.

Table 4.22: Load and segment masses

Loads Description	Load Mass (kg)	
	Worker 1	Worker 2
Rim-board Item 2 (Weight=36.2 lbs)	16.43	
Rim-board Item 5 (Weight=30.6 lbs)	13.89	
Joists Item 1 (All carried in one trip. Total Weight = 9.24 * 7 = 64.68 lbs)	29.36	
Rim-board Item 1 (Weight=61.2 lbs)		27.78
Rim-board Item 4 (Weight=36.2 lbs)		16.43
Rim-board Item 3 (Weight=134.4 lbs)	30.51	30.51
Joist item 2 (Weight=77.95 lbs)	17.69	17.69
Joist Item 3 (Weight=87.8 lbs)	19.93	19.93
All sheathing required (14 boards. Weight carried = 52.8 lbs per trip)		23.97
Nail Gun (13.8 lbs).	6.27	6.27
Upper-arm Segment (M_{UA})	4.38	4.92
Lower-arm/Hand Segment (M_{LA})	3.75	4.22
Head/Neck Segment (M_{HN})	6.24	6.91
Upper-back Segment (M_{UB})	37.04	41.95
No Load	6.27	0

Table 4.23: Typical segment angles adopted for each activity

Activities	Sub Activities	Worker	Segment Angles: Upper-arm	Lower-arm	Head/ Neck	Upper-back	
Bring Components from Storage (1or both Workers)	Walk to Component Storage	Worker 1	90	90	0	0	
		Worker 2	90	90	0	0	
	Reach to touch component	Worker 1	0	0	0	0	
		Worker 2	8	8	0	0	
	Lift component to neutral posture	Worker 1	75	60	0	0	
		Worker 2	75	60	0	0	
	Carry Component	Worker 1	75	60	0	0	
		Worker 2	75	60	0	0	
	Lower Component onto table	Worker 1	83	83	48	37	
		Worker 2	85	85	42	36	
Nailing Rim-board or Sheathing		Worker 1	40	40	57	78	
		Worker 2	43	43	37	32	
Bring Sheathing from Stack	Walk to Sheathing Stack/Pile	Worker 2	90	90	0	0	
	Bending to touch Sheathing Board	Worker 2	23	23	67	83	Worst Scenario chosen
	Lift Sheathing to neutral posture	Worker 2	68	68	12	12	
	Carry Sheathing	Worker 2	68	68	12	12	
	Lower Sheathing onto table	Worker 2	85	85	42	36	
Standing Posture (Arms by Side)		Worker 1	90	90	0	0	
		Worker 2	90	90	0	0	

Table 4.24: Resultant maximum dynamic lift strength $F_{MVC(N)}$

Sub-Activity	**Worker 1**	**Worker 2**
Walk to Component Storage	552.92	588.98
Reach For Component	214.36	230.69
Lift Component	519.94	349.92
Carry Component to Station	519.94	588.98
Lower Component onto Table	539.68	563.94
Walk to Sheathing Stack		588.98
Bend to touch Sheathing		247.37
Lift Sheathing		487.29
Carry Sheathing to Station		588.98
Lower Sheathing onto Table		555.66
Nail Rim-board or Sheathing	266.27	362.84
Neutral Standing Posture	552.92	588.98

Peak Dynamic Lift Strength (F_{MVC}) = 601N; Age Factors: Worker 1=0.92; Worker 2 = 0.98. Sex Factor = 1 for males

(5) Ergonomic Analysis

Ergonomic analysis is conducted based on biomechanical analyses of reaction forces and moments on the body segments and compression and shear forces, and stress on the lower-back L5-S1 disc. This is executed by applying the ErgoBioMCheck model described in Section 3.2.3. The major risk factors considered by this model are:

- Awkward postures
- Static and dynamic loads on the lower-back

The body segments assessed are:

- Head and neck
- Upper-back
- Upper-arm
- Lower-arm

Results and Discussion

The results of the analysis are presented in Table 4.25 - Table 4.26. Figure 4.19 - Figure 4.26 represent graphically the forces and moments for each worker for each activity grouping. Table 4.25 summarizes the estimated resultant forces and moments for each activity. Table 4.26 shows that the sheathing lift task exposes the worker to a compressive force 36% above the National Institute for Occupational Safety and Health (NIOSH)-recommended value. Also, in comparing the estimated lower-back forces with recommended lower-back lifting strength for the target anthropometry (Table 4.26), it can be seen that all the activities require lower-back contraction forces above the voluntary force postulated by Kumar's (2001) experiments.

The cumulative compressive and shear stress values estimated only take into consideration the lifting, lowering, and carrying activities. Figure 4.27 - Figure 4.28 show the estimated cumulative lower-back shear and compressive stresses based on the assessment results. Comparing the results with the lifetime cumulative load of Kumar (2001) on the L5/S1 disc corresponding to the pain group for men, it can be seen that the mean lifetime cumulative compressive load of up to 650±30 MN.s in Kumar (2001) is exceeded by two years by Worker 1 and by 5 months by Worker 2 in the current study. Also, Worker 2 exceeds the cumulative shear stress of 90±2MN.s corresponding to the pain group by 8 months if working continuously within the assessed conditions. This explains why cases of lifting tasks assessed as within safe limits still result in high incidence of LBP reports and claims. It can be seen that the current work conditions are unsafe and pose a high potential of resulting in incidents of work-related LBP (an example of a WRMSD).

Table 4.25: Estimated resultant forces and moments for each activity

Task	Worker	F_{SH} (N)	τ_{SH} (NM)	F_{LB} (N)	τ_{LB} (NM)	F_{EXT} (N)	F_{AB} (N)	F_{COMP} (N)	F_{SHEAR} (N)	Duration (s)	hand load weight (kg)	Item
Walk to Component Storage	Worker 1	79.76	0.00	504.33	0.00	0.00	0.00	504.33	0.00	120	0.00	
	Worker 2	89.66	0.00	568.98	0.00	0.00	0.00	568.98	0.00	120	0	
Reach For Component	Worker 1	80.99	24.50	505.57	24.73	494.62	8.58	990.99	0.62	2	0	
	Worker 2	91.16	29.80	570.48	30.10	601.97	12.22	1159.48	0.75	2	0	
Lift Components	Worker 1	243.99	16.73	668.57	17.18	343.57	4.45	1006.47	1.21	3	16.43	Rim-board2
	Worker 2	366.15	20.04	845.47	20.73	414.51	6.24	1252.00	1.73	3	27.78	Rim-board 1
	Worker 1	218.67	16.73	643.25	17.12	342.41	4.43	980.18	1.05	3	13.89	Rim-board 5
	Worker 2	253.39	20.04	732.71	20.48	409.61	6.11	1135.09	1.12	3	16.43	Rim-board 4
	Worker 1	372.89	16.73	797.46	17.47	349.48	4.59	1140.34	2.01	3	29.36	Joist 1
	Worker 2	393.28	20.04	872.59	20.78	415.69	6.27	1280.12	1.88	3	30.51	Rim-board 3
	Worker 1	384.35	16.73	808.93	17.50	350.00	4.60	1152.24	2.08	3	30.51	
	Worker 2	265.91	20.04	745.22	20.51	410.15	6.13	1148.07	1.18	3	17.69	Joist 2
	Worker 1	256.55	16.73	681.13	17.21	344.14	4.47	1019.52	1.29	3	17.69	
	Worker 2	288.16	20.04	767.48	20.56	411.12	6.15	1171.14	1.31	3	19.93	Joist 3
	Worker 1	278.88	16.73	703.46	17.26	345.17	4.49	1042.71	1.43	3	19.93	
Carry Component to Station	Worker 1	240.93	0.00	665.51	0.00	0.00	0.00	665.51	0.00	90	16.43	Rim-board2
	Worker 2	362.19	0.00	841.50	0.00	0.00	0.00	841.50	0.00	90	27.78	Rim-board 1
	Worker 1	216.02	0.00	640.59	0.00	0.00	0.00	640.59	0.00	90	13.89	Rim-board 5
	Worker 2	250.84	0.00	730.16	0.00	0.00	0.00	730.16	0.00	90	16.43	Rim-board 4
	Worker 1	367.78	0.00	792.35	0.00	0.00	0.00	792.35	0.00	90	29.36	Joist 1
	Worker 2	388.97	0.00	868.28	0.00	0.00	0.00	868.28	0.00	90	30.51	Rim-board 3
	Worker 1	379.06	0.00	803.64	0.00	0.00	0.00	803.64	0.00	90	30.51	
	Worker 2	263.20	0.00	742.52	0.00	0.00	0.00	742.52	0.00	90	17.69	Joist 2
	Worker 1	253.29	0.00	677.87	0.00	0.00	0.00	677.87	0.00	90	17.69	
	Worker 2	285.18	0.00	764.49	0.00	0.00	0.00	764.49	0.00	90	19.93	Joist 3

	Worker 1	275.27	0.00	699.85	0.00	0.00	0.00	699.85	0.00	90	19.93	

Task	**Worker**	**F_{SH} (N)**	**τ_{SH} (NM)**	**F_{LB} (N)**	**τ_{LB} (NM)**	**F_{EXT} (N)**	**F_{AB} (N)**	**F_{COMP} (N)**	**F_{SHEAR} (N)**	**Duration (s)**	**hand load weight (kg)**	**Item**
Lower Component onto Table	Worker 1	241.24	13.71	666.08	59.66	1193.17	28.90	1762.53	201.18	3	16.43	Rim-board2
	Worker 2	362.71	17.43	842.35	71.91	1438.22	40.94	2158.15	248.59	3	27.78	Rim-board 1
	Worker 1	216.27	13.71	641.11	59.63	1192.57	28.87	1739.54	193.62	3	13.89	Rim-board 5
	Worker 2	251.13	17.43	730.77	71.78	1435.57	40.80	2054.92	215.60	3	16.43	Rim-board 4
	Worker 1	368.37	13.71	793.21	59.81	1196.27	29.03	1879.58	239.69	3	29.36	Joist 1
	Worker 2	389.55	17.43	869.18	71.94	1438.86	40.97	2182.98	256.53	3	30.51	Rim-board 3
	Worker 1	379.68	13.71	804.52	59.83	1196.54	29.05	1889.99	243.11	3	30.51	Rim-board 3
	Worker 2	263.51	17.43	743.15	71.79	1435.87	40.82	2066.38	219.26	3	17.69	Joist 2
	Worker 1	253.63	13.71	678.47	59.67	1193.48	28.91	1773.94	204.94	3	17.69	Joist 2
	Worker 2	285.54	17.43	765.17	71.82	1436.39	40.85	2086.75	225.77	3	19.93	Joist 3
	Worker 1	275.65	13.71	700.49	59.70	1194.01	28.94	1794.22	211.61	3	19.93	Joist 3
Walk to Sheathing Stack	Worker 2	89.66	0.00	568.98	0.00	0.00	0.00	568.98	0.00	10	0	
Bending to touch Sheathing	Worker 2	92.17	46.53	576.79	137.99	2759.71	57.79	3025.25	286.49	2	0	
Lift Sheathing	Worker 2	325.97	30.50	806.02	229.99	4599.83	427.35	4615.88	483.74	5	23.97	OSB Sheathing
Carry Sheathing to Station	Worker 2	324.81	0.00	804.13	26.88	537.51	8.96	1315.10	167.18	20	23.97	
Lower Sheathing onto Table	Worker 2	325.29	15.43	804.77	77.72	1554.46	47.09	2225.89	320.78	3	23.97	
Nailing Rim-board or Sheathing	Worker 1	141.65	18.57	566.22	69.48	1389.62	19.11	1488.49	553.64	5	6.27	
	Worker 2	151.17	0.00	630.49	31.88	637.63	9.92	1162.40	334.09	5	6.27	
Neutral Standing Posture	Worker 1	79.76	0.00	504.33	0.00	0.00	0.00	504.33	0.00	1200	0	
	Worker 2	89.66	0.00	568.98	0.00	0.00	0.00	568.98	0.00	1200	0	

Table 4.26: Comparison of recommended maximum lower-back lifting (F_{MVC}) and compressive forces (F_{COMP}) with estimated lifting (F_{ACT}) and compressive forces for observed activities

Task	Worker	F_{LB} (N)	Recommended Max Force	% of Recommended Max	Remarks	F_{COMP} (N)	F_{SHEAR} (N)	NIOSH Recommendation for F_{COMP}	% of Recommended Max	Remarks
Lift Components	Worker 1	668.57	506.919	132%	Over	1006.47	1.21	3400.00	30%	Safe
	Worker 2	845.47	447.246	189%	Over	1252.00	1.73	3400.00	37%	Safe
	Worker 1	643.25	506.919	127%	Over	980.18	1.05	3400.00	29%	Safe
	Worker 2	732.71	447.246	164%	Over	1135.09	1.12	3400.00	33%	Safe
	Worker 1	797.46	506.919	157%	Over	1140.34	2.01	3400.00	34%	Safe
	Worker 2	872.59	447.246	195%	Over	1280.12	1.88	3400.00	38%	Safe
	Worker 1	808.93	506.919	160%	Over	1152.24	2.08	3400.00	34%	Safe
	Worker 2	745.22	447.246	167%	Over	1148.07	1.18	3400.00	34%	Safe
	Worker 1	681.13	506.919	134%	Over	1019.52	1.29	3400.00	30%	Safe
	Worker 2	767.48	447.246	172%	Over	1171.14	1.31	3400.00	34%	Safe
	Worker 1	703.46	506.919	139%	Over	1042.71	1.43	3400.00	31%	Safe
Carry Component to Station	Worker 1	665.51	506.919	131%	Over	665.51	0.00	3400.00	20%	Safe
	Worker 2	841.50	588.98	143%	Over	841.50	0.00	3400.00	25%	Safe
	Worker 1	640.59	506.919	126%	Over	640.59	0.00	3400.00	19%	Safe
	Worker 2	730.16	588.98	124%	Over	730.16	0.00	3400.00	21%	Safe
	Worker 1	792.35	506.919	156%	Over	792.35	0.00	3400.00	23%	Safe
	Worker 2	868.28	588.98	147%	Over	868.28	0.00	3400.00	26%	Safe
	Worker 1	803.64	506.919	159%	Over	803.64	0.00	3400.00	24%	Safe
	Worker 2	742.52	588.98	126%	Over	742.52	0.00	3400.00	22%	Safe
	Worker 1	677.87	506.919	134%	Over	677.87	0.00	3400.00	20%	Safe
	Worker 2	764.49	588.98	130%	Over	764.49	0.00	3400.00	22%	Safe
	Worker 1	699.85	506.919	138%	Over	699.85	0.00	3400.00	21%	Safe
Lower Component onto Table	Worker 1	666.08	539.678	123%	Over	1762.53	201.18	3400.00	52%	Safe
	Worker 2	842.35	552.358	153%	Over	2158.15	248.59	3400.00	63%	Safe
	Worker 1	641.11	539.678	119%	Over	1739.54	193.62	3400.00	51%	Safe
	Worker 2	730.77	552.358	132%	Over	2054.92	215.60	3400.00	60%	Safe
	Worker 1	793.21	539.678	147%	Over	1879.58	239.69	3400.00	55%	Safe
	Worker 2	869.18	552.358	157%	Over	2182.98	256.53	3400.00	64%	Safe
	Worker 1	804.52	539.678	149%	Over	1889.99	243.11	3400.00	56%	Safe
	Worker 2	743.15	552.358	135%	Over	2066.38	219.26	3400.00	61%	Safe
	Worker 1	678.47	539.678	126%	Over	1773.94	204.94	3400.00	52%	Safe
	Worker 2	765.17	552.358	139%	Over	2086.75	225.77	3400.00	61%	Safe
	Worker 1	700.49	539.678	130%	Over	1794.22	211.61	3400.00	53%	Safe
Bending to touch Sheathing	Worker 2	576.79	568.98	101%	Over	3025.2515	286.487	3400.00	89%	Safe
Lift Sheathing	Worker 2	806.02	349.904	230%	Over	4615.88	483.74	3400.00	136%	Unsafe
Carry Sheathing	Worker 2	804.13	588.98	137%	Over	1315.10	167.18	3400.00	39%	Safe
Lower Sheathing	Worker 2	804.77	547.022	147%	Over	2225.89	320.78	3400.00	65%	Safe

Age Factors: Worker 1=0.92; Worker 2 = 0.98. Sex Factor = 1 for males. The reach factor is estimated based on the distance of hand load to shoulder axis

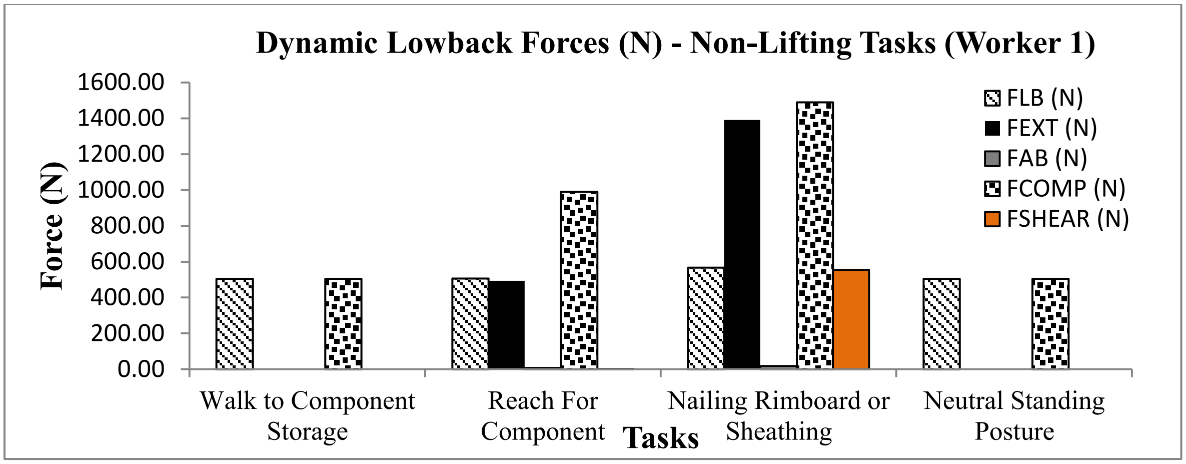


Figure 4.19: Dynamic lower-back forces estimated for non-lifting tasks (Worker 1)

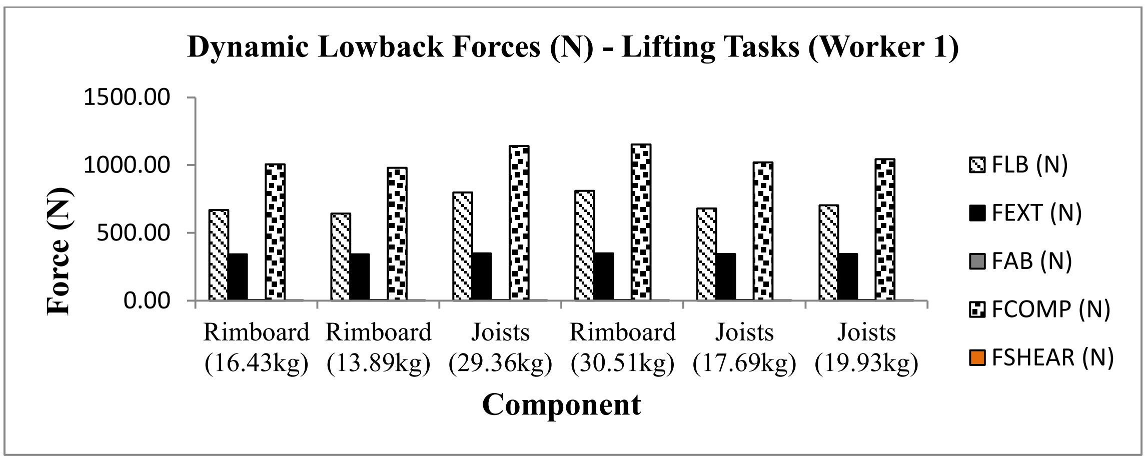


Figure 4.20: Dynamic lower-back forces estimated for lifting tasks (Worker 1)

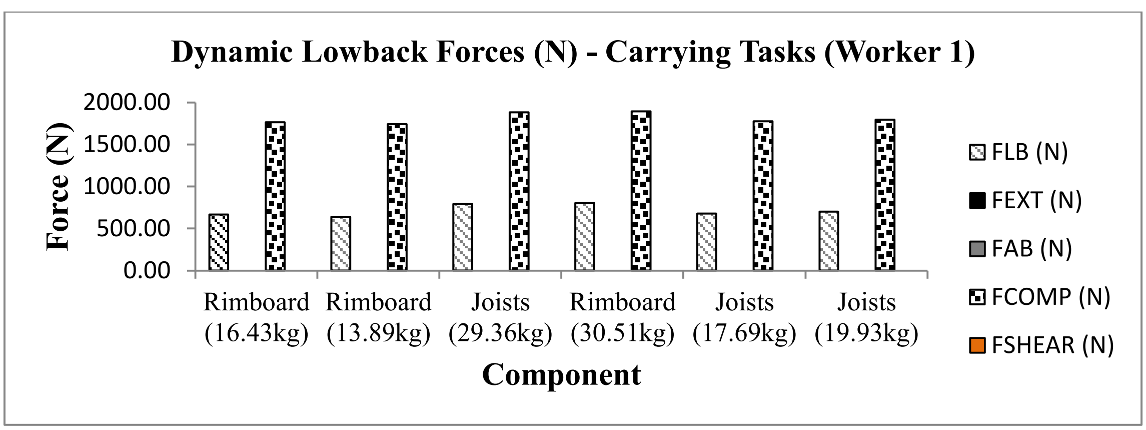


Figure 4.21: Dynamic lower-back forces estimated for carrying tasks (Worker 1)

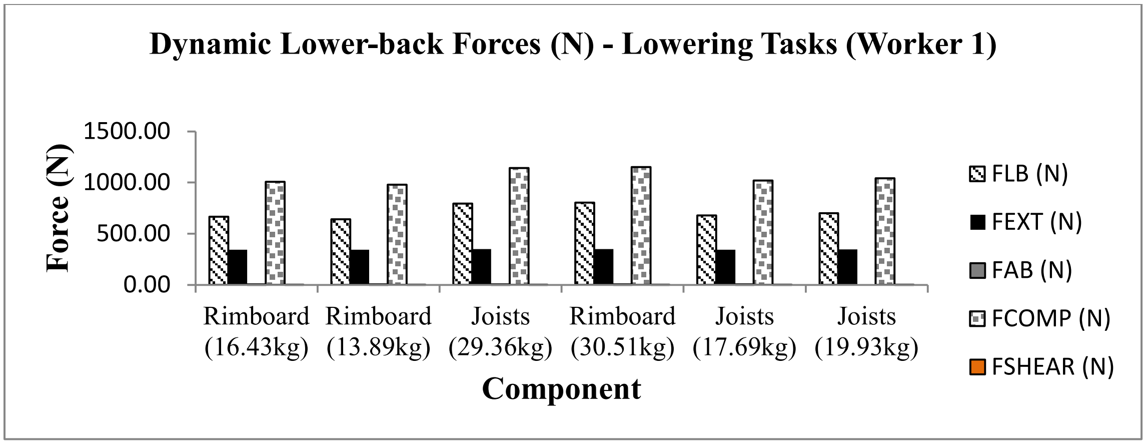


Figure 4.22: Dynamic lower-back forces estimated for lowering tasks (Worker 1)

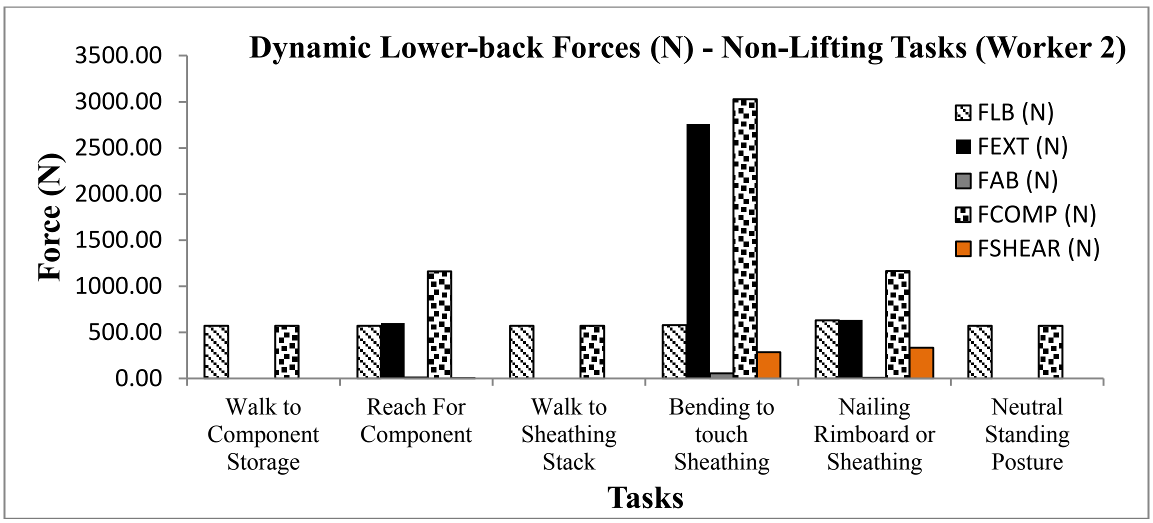


Figure 4.23: Dynamic lower-back forces estimated for non-lifting tasks (Worker 2)

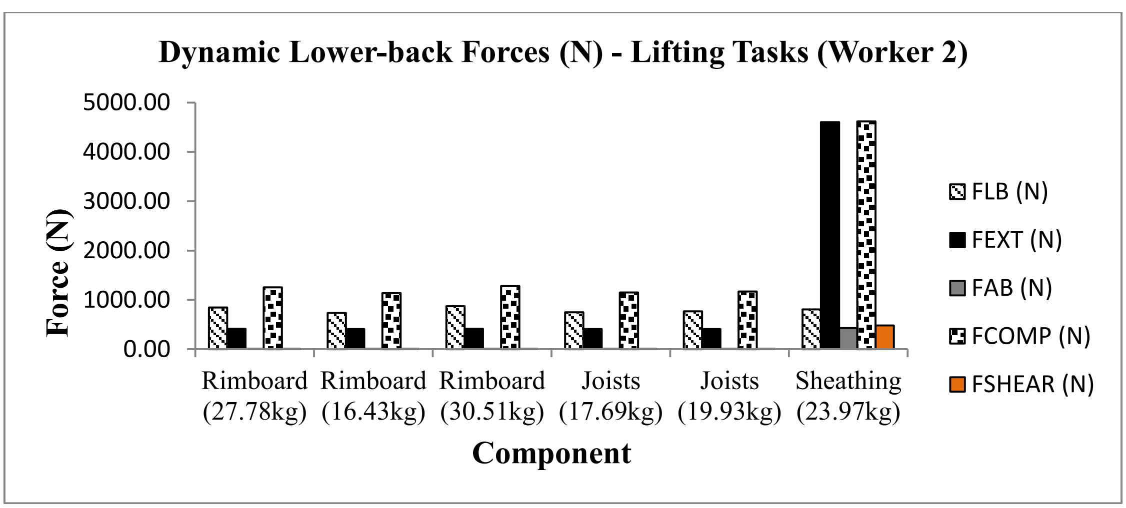


Figure 4.24: Dynamic lower-back forces estimated for lifting tasks (Worker 2)

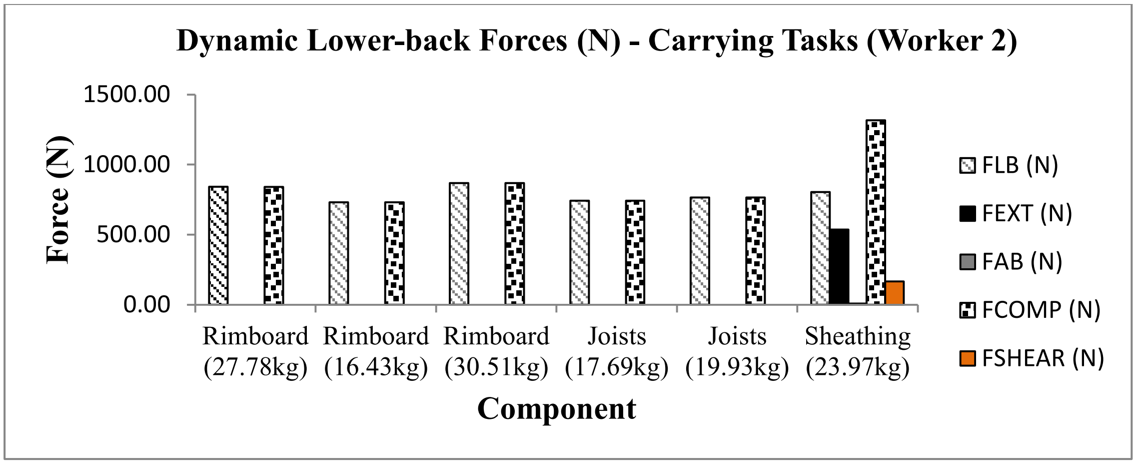


Figure 4.25: Dynamic lower-back forces estimated for carrying tasks (Worker 2)

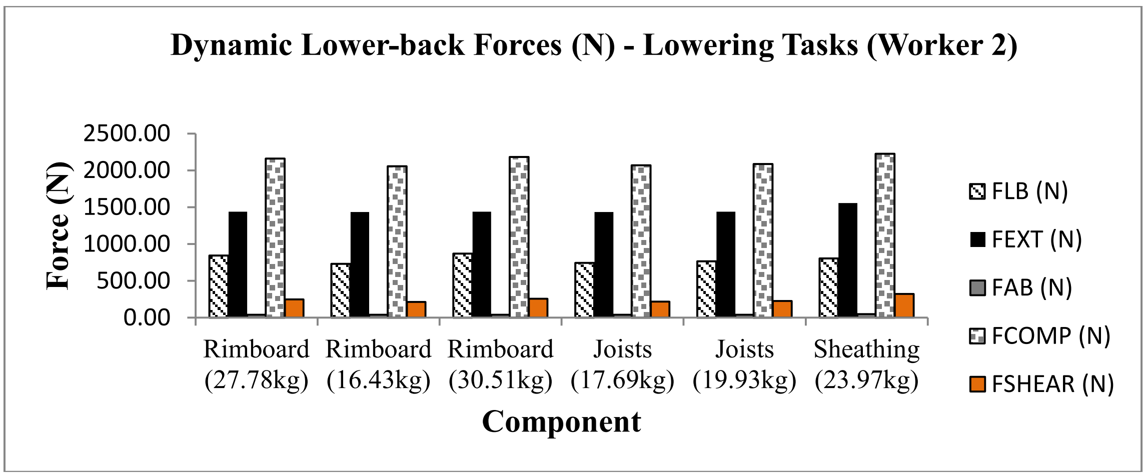


Figure 4.26: Dynamic lower-back forces estimated for lowering tasks (Worker 2)

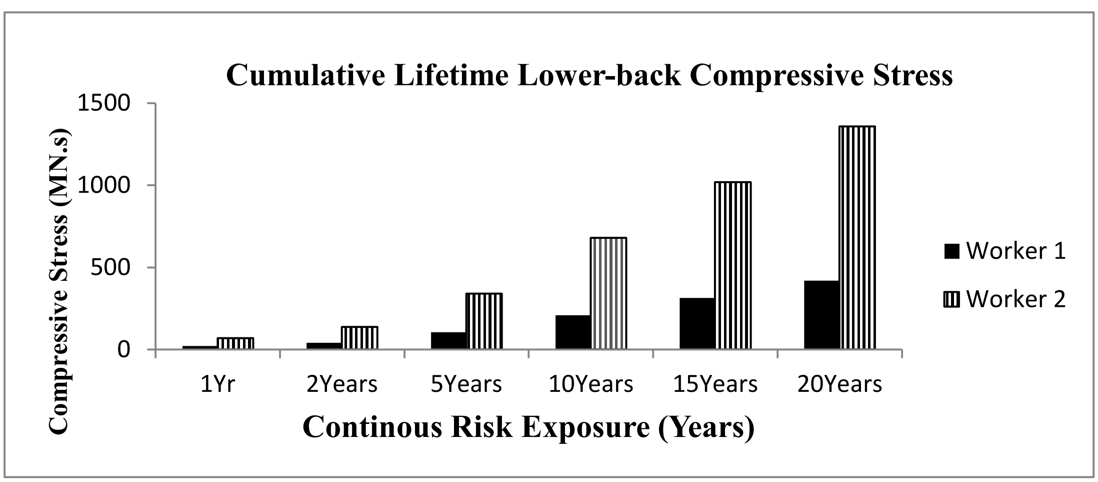


Figure 4.27: Potential cumulative lifetime lower-back compressive stresses

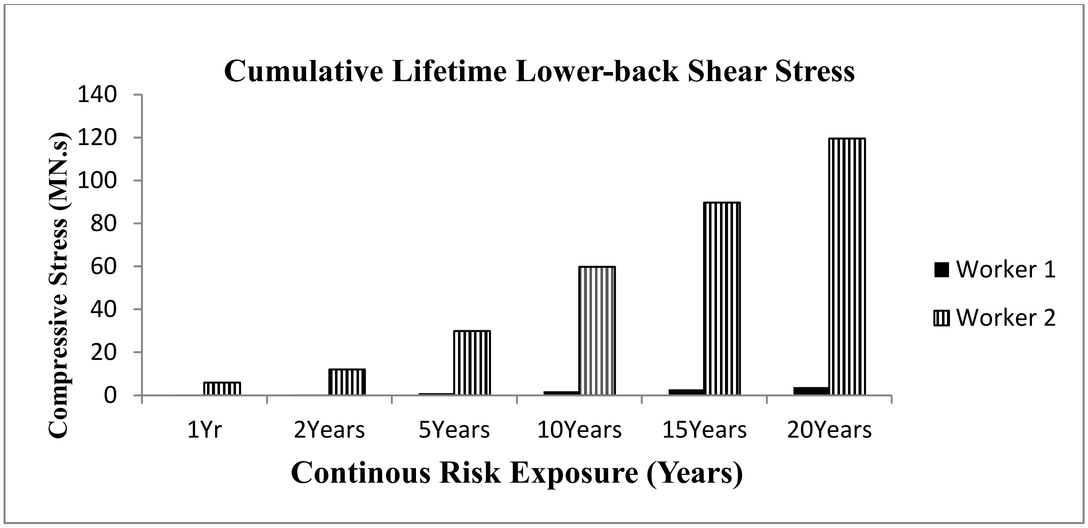


Figure 4.28: Potential cumulative lifetime lower-back shear stresses

Discussion and Recommendations

The results of the assessment show evidence of a high potential for the risk of lower-back injury from carrying activities involving sheathing. Also, the cumulative stress assessment results shows that the task of floor framing poses a very high risk of developing low back pain (LBP) within a very short time. Based on the above results, engineering controls are recommended to replace the heavy lifting activities.

As of April, 2011, the Landmark factory has applied engineering controls to eliminate the identified high-risk activities through the introduction of an overhead crane to transport the components from storage to the work area as well as a mechanical vacuum lift system (Figure 4.44) to eliminate the manual process of carrying the sheathing. This has resulted in a safer workplace and increased productivity.

Model Validation

Apart from the biomechanical and kinematics-bases used to formulate the model, further validation has been conducted by comparing the results obtained by the model with those of a popular human modelling and ergonomic analysis program, 3DSSPP (University of Michigan 2003). The input values for this model included worker anthropometry, work postures, and external load information as used in this case study.

3DSSPP is a static strength (biomechanical and digital human model) which offers both postural and biomechanical load analysis functionalities and is used for proactive ergonomic analysis of the biomechanical risk for injury based on the proposed workplace design (Feyen et al. 2000; Ma et al. 2009). Although the use of this model has limitations and introduces potential errors when assessing dynamic cases, since the developed model describes certain activities as static (when the same posture is maintained over assessed time interval), and since both models are based on biomechanical analysis and are intended for proactive analysis, it is deemed suitable for use in validation purposes subject to its limitations. Also, contributing to its selection was the ease of use of this software and the option of downloading a limited-duration trial version of the software rather than purchasing a full version.

Figure 4.29 - Figure 4.40 show a comparison between model estimates with 3DSSPP for shoulder, lower-back, abdominal, compression, and shear forces and moments.

The results show a high level of agreement in the estimation of shoulder forces for both Worker 1 and Worker 2 (Figure 4.29 and Figure 4.35). The model estimates slightly higher lower-back forces for both workers (Figure 4.30 and Figure 4.36). The estimated mean percent differences (percent errors) of 18% (Worker 1) and 22% (Worker 2) between the static 3DSSPP estimate and the biomechanical model estimate are in accordance with research conclusions, suggesting that static analysis underestimates lower-back forces since acceleration components are not taken into consideration in static estimations of lower-back forces (Merryweather and Bloswick 2008; Leskinen et al. 1983).

Figure 4.31 and Figure 4.37 show the comparison of lower-back compressive force estimates between the model and 3DSSPP. It can be seen that, in most cases (14% error for Worker 1 and 9% error for Worker 2), the 3DSSPP estimates higher magnitudes of lower-back compression than the model. This is to be expected as the static assessment considers only one (1) posture and loading case (and this is the most critical state of the assessment), while the developed model assesses the average compressive load due to the transition from initial to current posture and loading states over the activity period.

The same relationship is seen in the comparison of the torque estimations for the shoulder and lower-back (Figure 4.32, Figure 4.34, Figure 4.38, Figure 4.40) and the abdominal muscle force (Figure 4.33, Figure 4.39). The comparison confirms that static estimations of shoulder and lower-back may lead to an overestimation of risk magnitude and thus may result in a negative impact on productivity.

Furthermore, a comparison between the model shear force estimate and that of the 3DSSPP model shows no conformance for any loading scenario for either Worker 1 or Worker 2. The basis for the estimation of shear force for asymmetrical loading by the 3DSSPP program needs to be further researched, as this may be the key to the lack of correlation in the results.

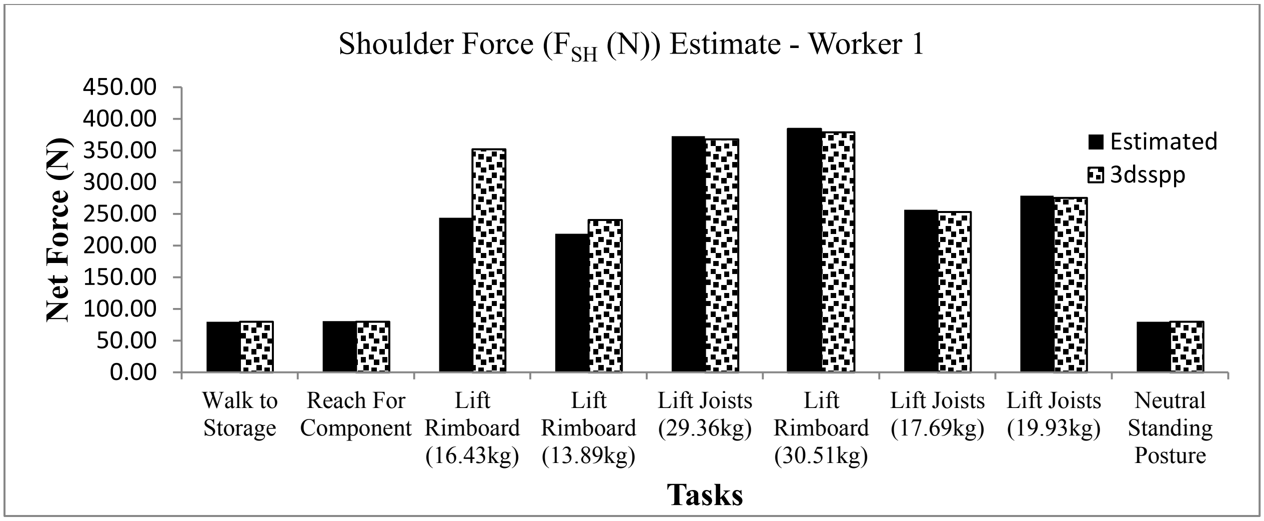


Figure 4.29: Comparison of estimated shoulder force with 3DSSPP model software (Worker 1)

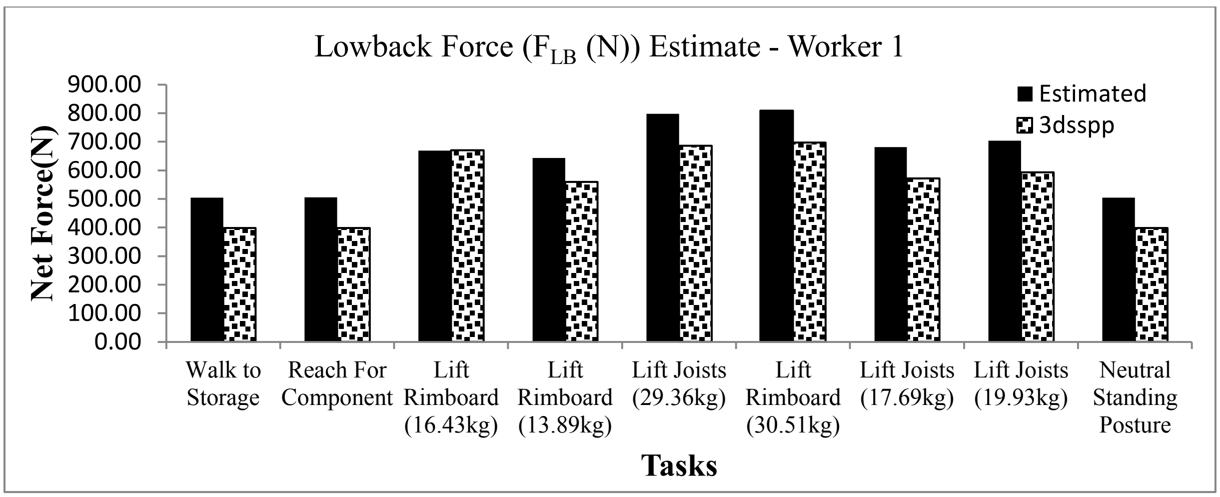


Figure 4.30: Comparison of estimated lower-back force with 3DSSPP model software (Worker 1)

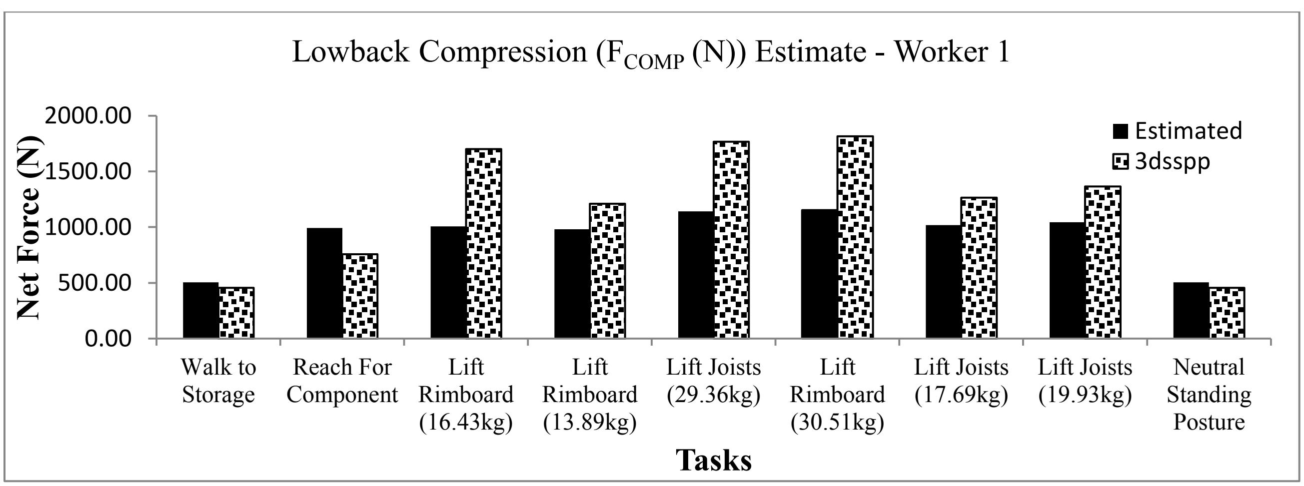


Figure 4.31: Comparison of estimated compressive force with 3DSSPP model software (Worker 1)

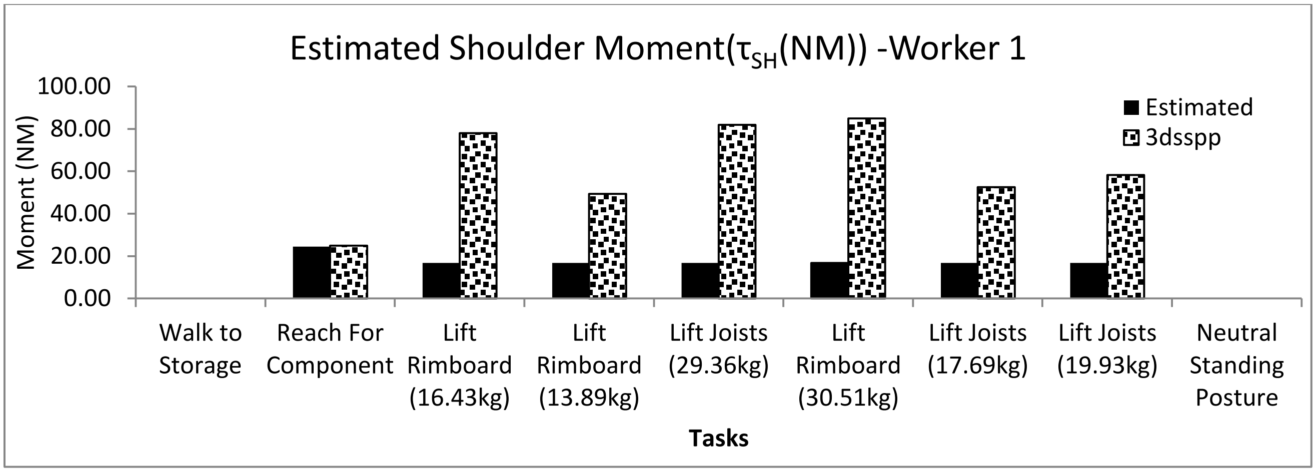


Figure 4.32: Comparison of estimated shoulder moments with 3DSSPP model software (Worker 1)

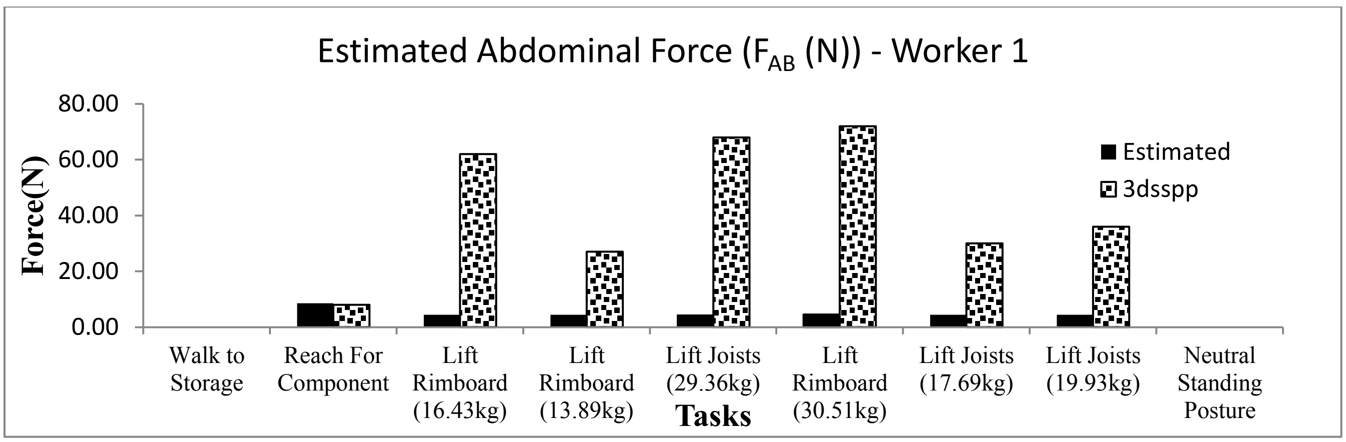


Figure 4.33: Comparison of abdominal force estimates with 3DSSPP model software (Worker 1)

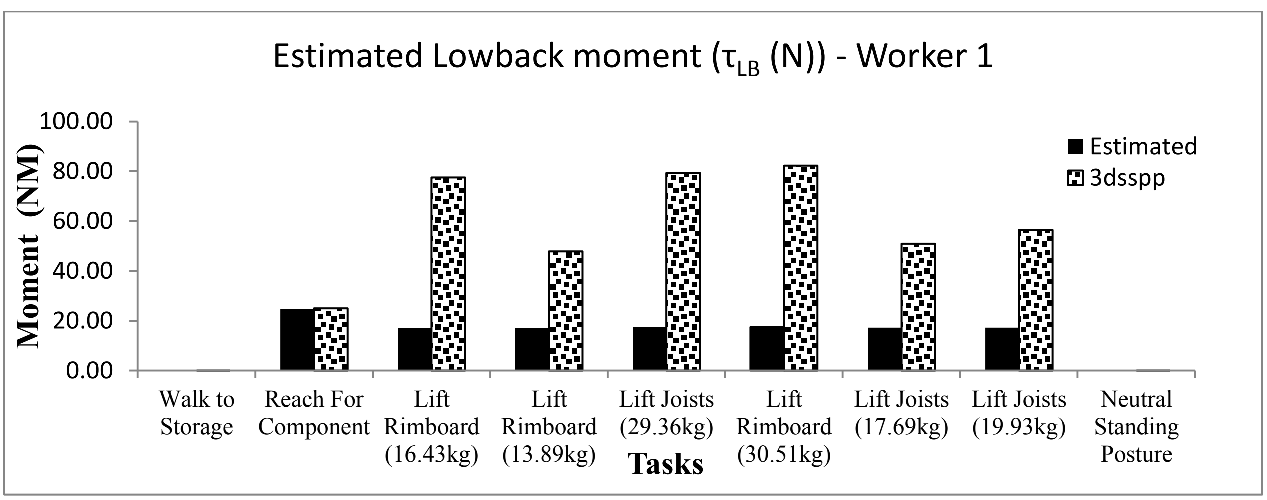


Figure 4.34: Comparison of estimated lower-back moments with 3DSSPP model software (Worker 1)

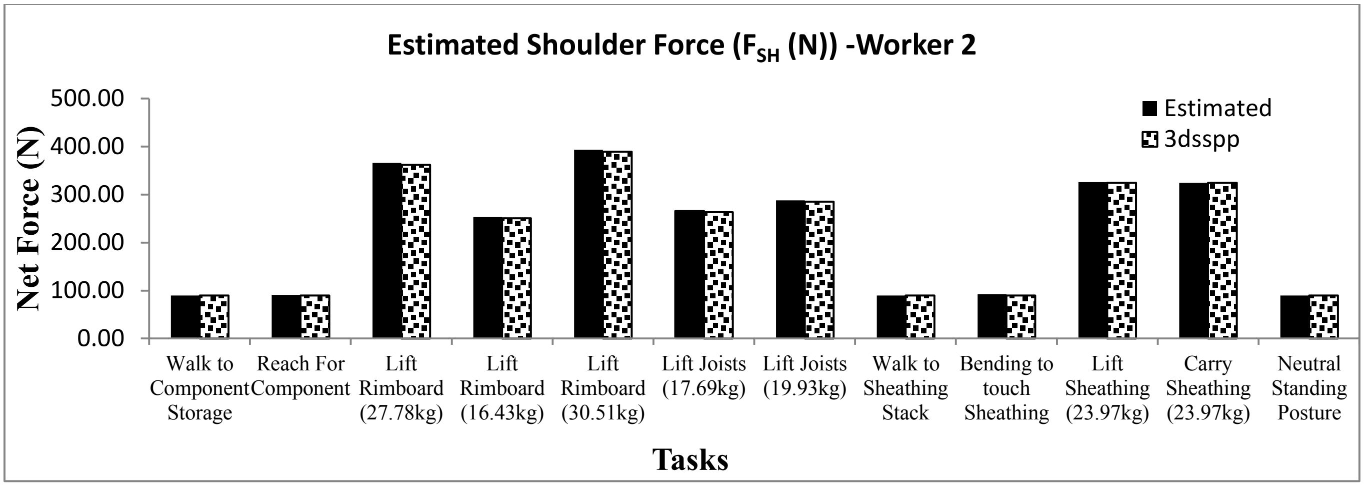


Figure 4.35: Comparison of estimated shoulder force with 3DSSPP model software (Worker 2)

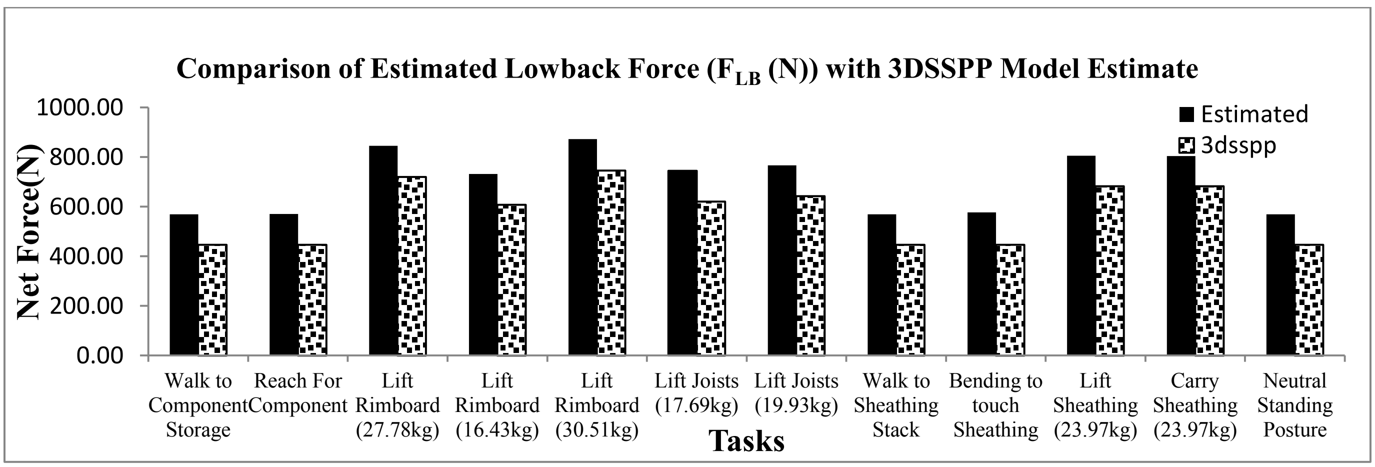


Figure 4.36: Comparison of estimated lower-back force with 3DSSPP model software (Worker 2)

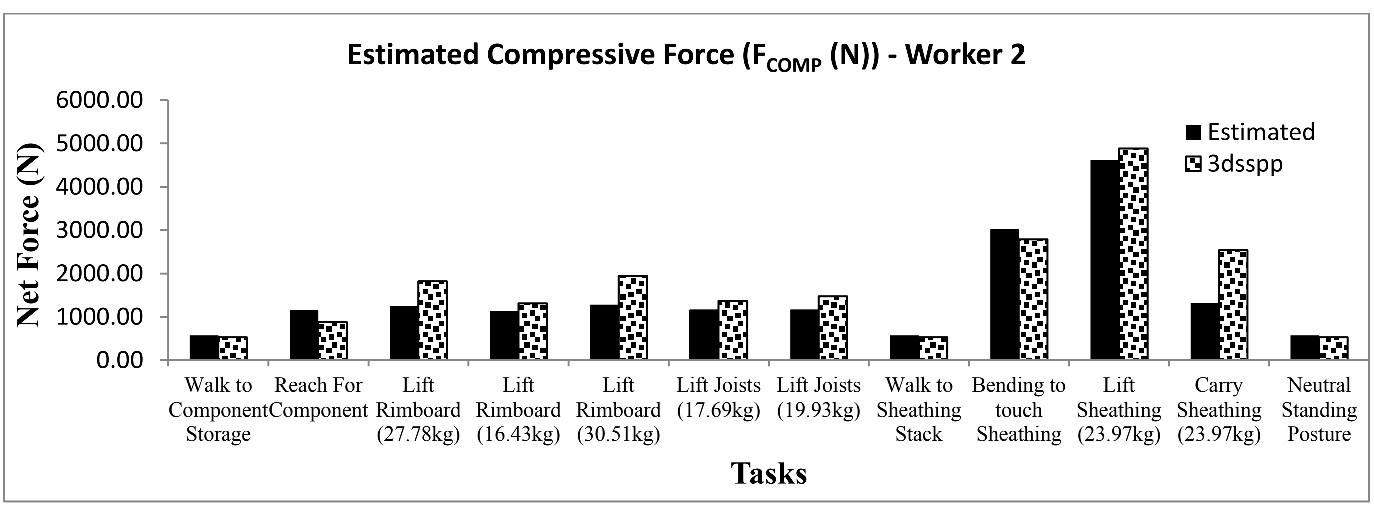


Figure 4.37: Comparison of estimated compressive force with 3DSSPP model software (Worker 2)

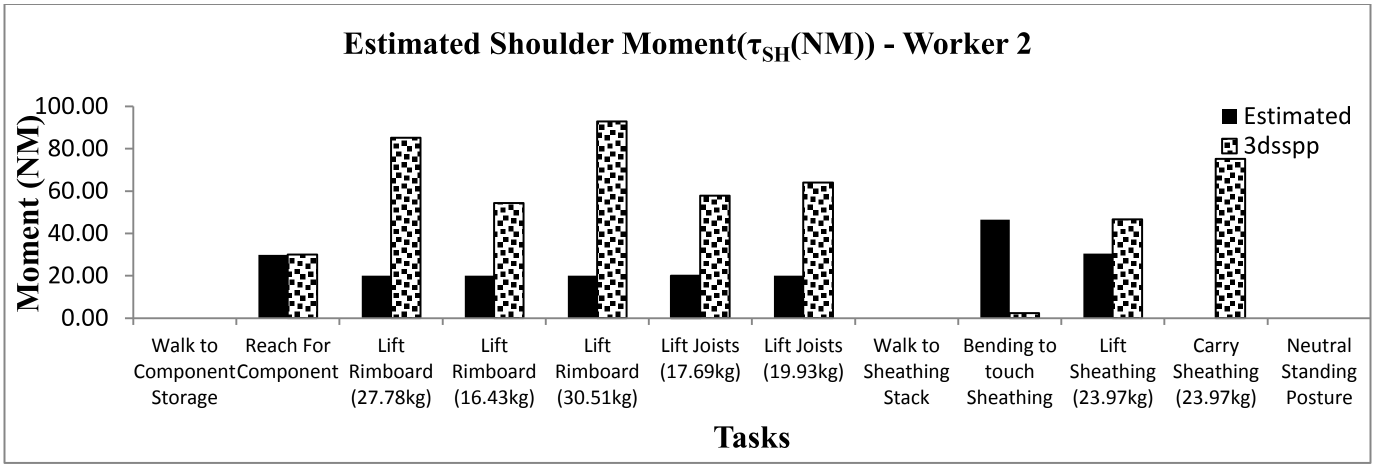


Figure 4.38: Comparison of estimated shoulder moments with 3DSSPP model software (Worker 2)

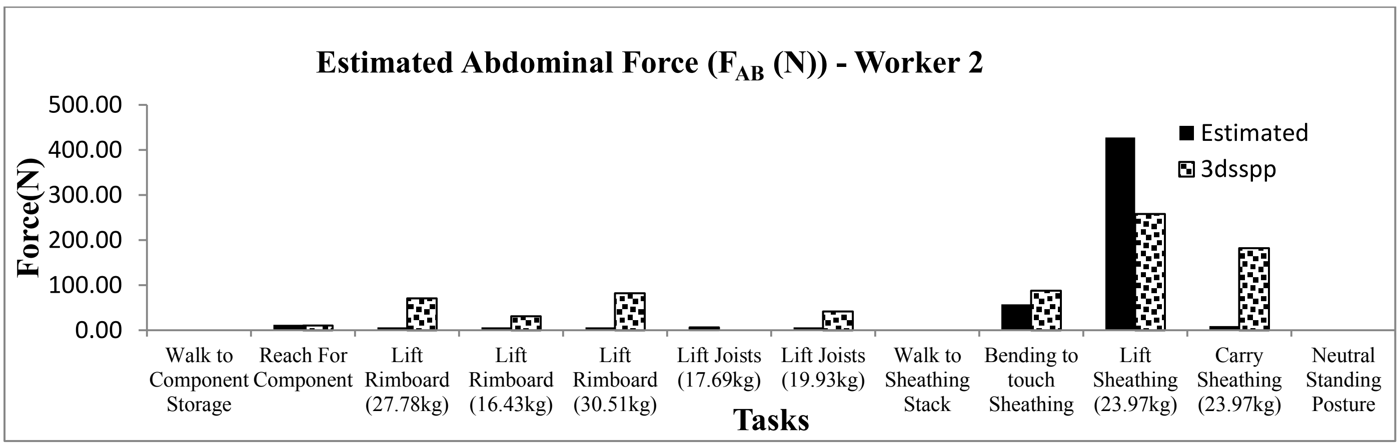


Figure 4.39: Comparison of abdominal force estimates with 3DSSPP model software (Worker 2)

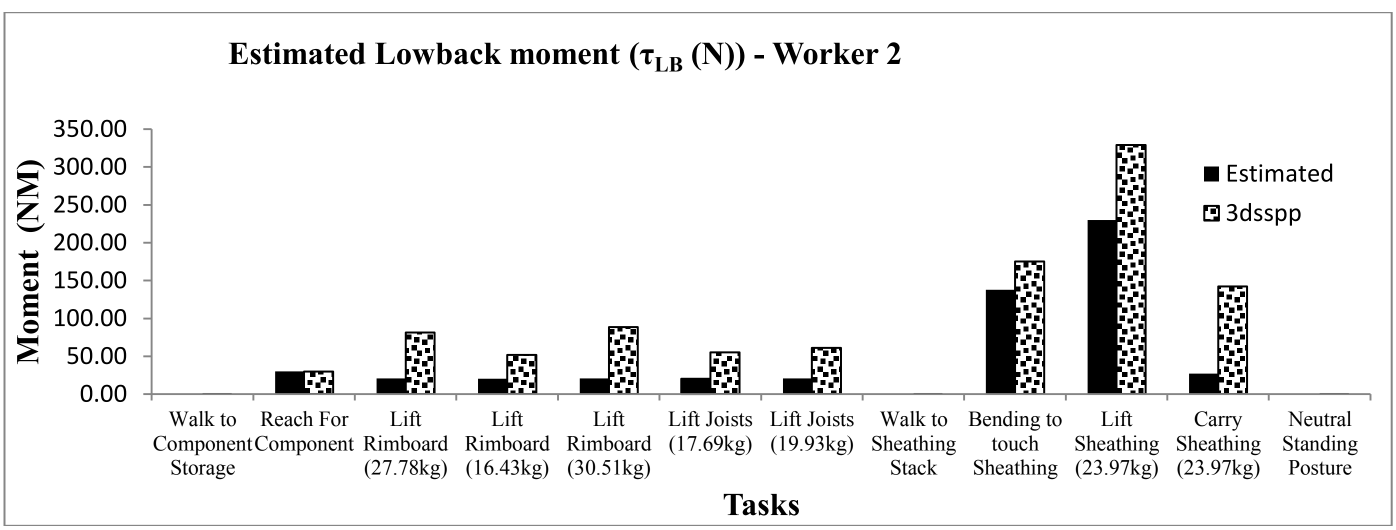


Figure 4.40: Comparison of estimated lower-back moments with 3DSSPP model software (Worker 2)

The results of the comparison give reasonable confidence and highlight the capability of the developed model to assess shoulder and lower-back biomechanical forces and moments resulting from dynamic work activities. Further validation is recommended comparing the model estimates with direct assessment methods in order to fully ascertain the closeness of the model with actual compression scenarios. This is important given that the estimation of cumulative impact of loading is a key to understanding the development of cumulative trauma disorders such as back pain due to work activities.

Case 5: Discrete event simulation for ergonomic assessment of construction tasks.

Introduction and Overview of Case Study

The proposed DES model depicts the manual floor production line construction process for panelized residential construction as at the time of study (August, 2011). Since that time, the manual lifting activities have been replaced by engineering controls as presented in Case 4. This study focuses on the implementation of DES using Simphony's general template to assess the postural ergonomic risks resulting from manual floor framing tasks (Figure 4.41). Based on the ergonomic assessment results, the risk factors have been identified, and recommendations to lower the ergonomic risk have been incorporated into the DES model to observe their impact. These recommendations are intended to improve the already high safety standard established by Landmark.

Figure 4.41: 3D model of framing station

Background

The manual floor framing task involves significant nailing and cutting and is carried out on a pin table by two (2) framing carpenters. As shown in Figure 4.42, the reach and nature of the tasks require one or both carpenters to climb onto the pin table in order to work. This exposes them to increased risk from awkward bending (neck, back) and squatting postures.

Floor Framing Process: After receiving the work order, the carpenters check the drawings to determine the floor type to be framed in that day. One worker then proceeds to crane in the components (joists, rim-boards, and blocking) to the pin table (Figure 4.43.) from the component storage using overhead craning equipment. Once craning has been completed, the carpenters climb onto the table to assemble the components according to the specifications. The components are then nailed together to form the outer frame of the floor. The nailing of timber flows from the first to the last section as shown in Figure 4.45. Depending on the surface to be nailed, the carpenter may nail while squatting on the table or standing on the ground. Usually one carpenter stays on the table while the other nails from the ground (except when the activity demands both to be working from the same surface). Once nailing has been completed, adhesive is applied onto the top of the joists and rim-boards. The carpenter on the floor flies in the sheathing boards using a mechanical lift (Figure 4.44). The sheathing board is aligned on the floor frame by both workers and nailed according to the layout (as in Figure 4.46). After nailing on a given sheathing board, the carpenter returns to bring in the next board. This process continues in the same sequence until all sections are covered and nailed. For the case of craning for transport and site installation, holes are cut at predetermined locations on the timber and sheathing; this is necessary for attaching the crane strapping (Figure 4.45). Once all sheathing has been placed, the carpenters check for any areas that may need cutting, and the cutting activity is then executed. Finally, the floor is strapped and craned to the installation truck. The cleanup of cutting waste is performed and the carpenters move the crane for the next floor components. An average of four floors are framed each day by the crew.

Discrete Event Simulation Model Development Process

Using information from the specifications and the framing process, the DES model has been developed to closely represent the current work through three (3) main steps.

i. *Database Design*: A Microsoft Access database was created to store information required to design the simulation and visualization models. The database contained three (3) main tables. (a)-*ActivityPostures* (Appendix 0-15) documents all floor framing activities and the adopted work (neck, back, leg) postures. (b)-*ActivityWorkingRates* (Appendix 0-16) stores duration- and productivity-based (working rates) information pertaining to each activity. These rates are used to estimate the time for each activity based on work demand. (c)-*Floor* (Appendix 0-17-Appendix 0-21) stores floor design information such as requirements for nailing timber (joists, rim-boards, blocking) and sheathing, number of sections in each floor design, floor geometry, cutting and strapping positions, and nailing surfaces as shown in Figure 4.45 and Figure 4.46.

ii. *Process Simulation*: The framing process is modeled using the Simphony general template simulation for both the current and proposed layouts (Figure 4.47-Figure 4.51). The developed simulation model is linked to the database as its data source and the outputs of the simulation are written out automatically in comma delimited format.

iii. *Post Simulation Visualization Model (PSV) Development and Verification*: Using 3DS Max, a post simulation visualization model is developed to closely represent the actual framing process by incorporating the duration output from the Simphony simulation model and the postures adopted while performing different activities. The PSV model performs a dual capacity, serving as a source of ergonomic data collection by replacing the need for repeated onsite observation of the work and also verifying the simulation design. Ergonomic risk assessment of the work alternatives and recommendations can be executed by observing the PSV model during runtime. Han et al. (2011) have described a methodology for ergonomic assessment based on the ErgoCheck technique.

Figure 4.42: Limited reach and awkward postures

Figure 4.43: Joist and rim-board components being brought in by overhead crane

Figure 4.44: Mechanical vacuum lift system for flying in sheathing boards.

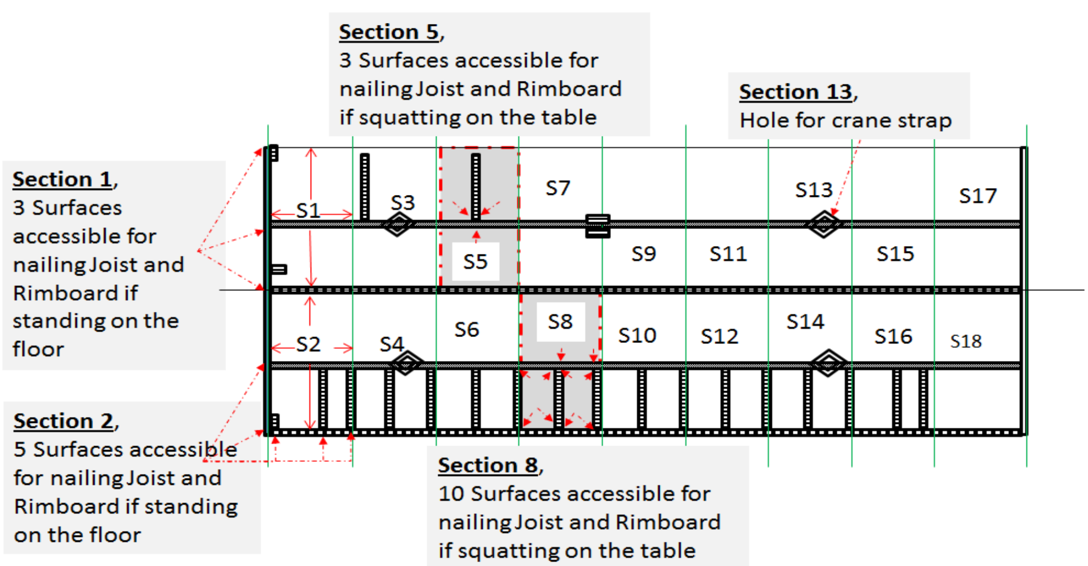


Figure 4.45: Timber nailing surfaces and sections

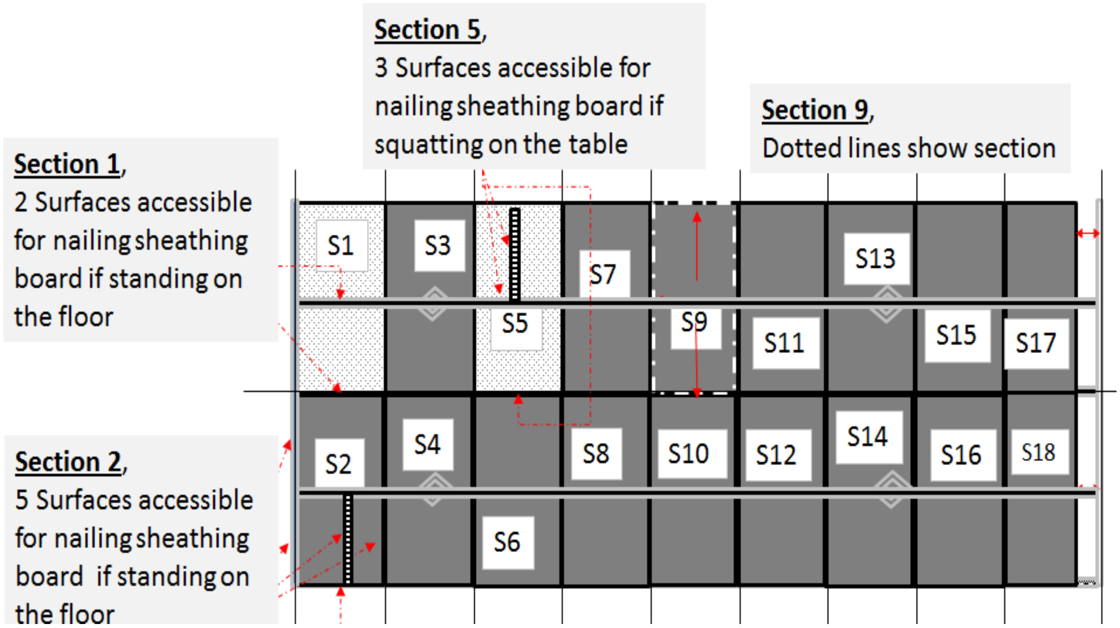


Figure 4.46: Sheathing nailing surfaces and sections

Results and Discussion

Results

This study focused on the ergonomic assessment of working postures adopted by the two floor framing carpenters. Emphasis was placed on awkward back postures (0-20° flexion, 20°-60° flexion and >60° flexion), neck postures (upright, 0-20° flexion, 20°-60° flexion, and >60° flexion) and leg postures (squatting or kneeling). Significant bending and squatting was necessitated due to the reach constraints for nailing and cutting tasks.

i. *Productivity Assessment*: The simulation records and exports time-stamped and event-based production output information which is suitable for productivity analysis. This is a measure of the resource-based productivity of the system. Table 4.27 shows the productivity assessment for both current and proposed work scenarios. It can be seen that, based on the current scenario, Floor 1 is completed in 130 minutes, Floor 2 in 73.3 minutes, Floor 3 in 65.2 minutes, and Floor 4 in 127.6 minutes.

ii. *Ergonomic Assessment*: Table 4.28: Postural exposure durations shows the summary of daily exposure durations of awkward exposure for each of the back, neck, and leg risks. Worker 1 is exposed to about 2 hours of squatting/kneeling, back flexion >60° and neck posture of 0-20° flexion in the course of work based on the current scenario and results in a medium risk classification for the back, neck, and legs for this worker.(Table 4.29)

Discussion

The results of the initial simulation lead to an embellishment of the simulation model (Figure Figure 4.48) and three (3) recommendations, outlined below:

(1) Replace manual framing activities with an automated system to eliminate prolonged exposure to awkward work postures.

(2) Redesign the pin table to allow a 3-foot space at the centre (Figure 4.52).

(3) Introduce a new cutting station (Figure 4.53).

Adoption of recommendation 1 will eliminate exposure to awkward work postures and hand forces since the activities will be machine-automated. Automation of the floor framing process is already in operation, executed using the multifunction framing bridge.

In order to improve the manual framing process the potential ergonomics and productivity impacts of Recommendations 2 and 3 will be reviewed using the DES model. The most efficient and optimal pin table redesign (dimensions and spacing) can be achieved with optimization techniques by assessing all the floor design models produced by the factory on the pin table. However, optimization has not been the focus of this study. To illustrate the proposed concept, the author has adopted a pin table redesign (spacing) which will grant Worker 2 more reach to floor surfaces and will also reduce the amount of time Worker 1 spends in awkward postures.

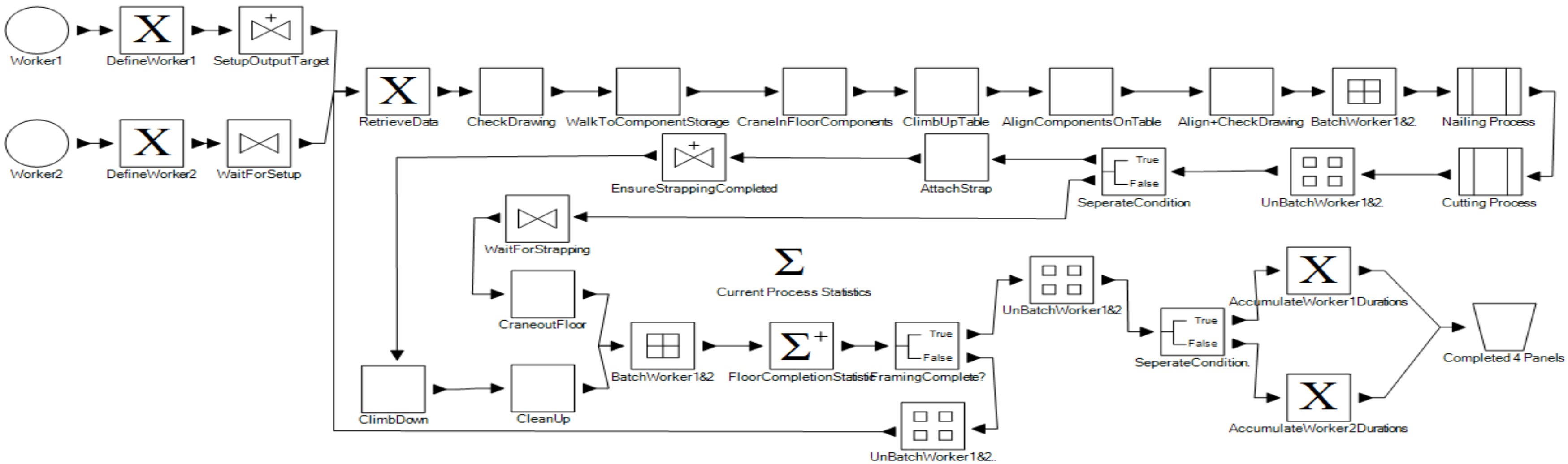


Figure 4.47: Current floor framing simulation model

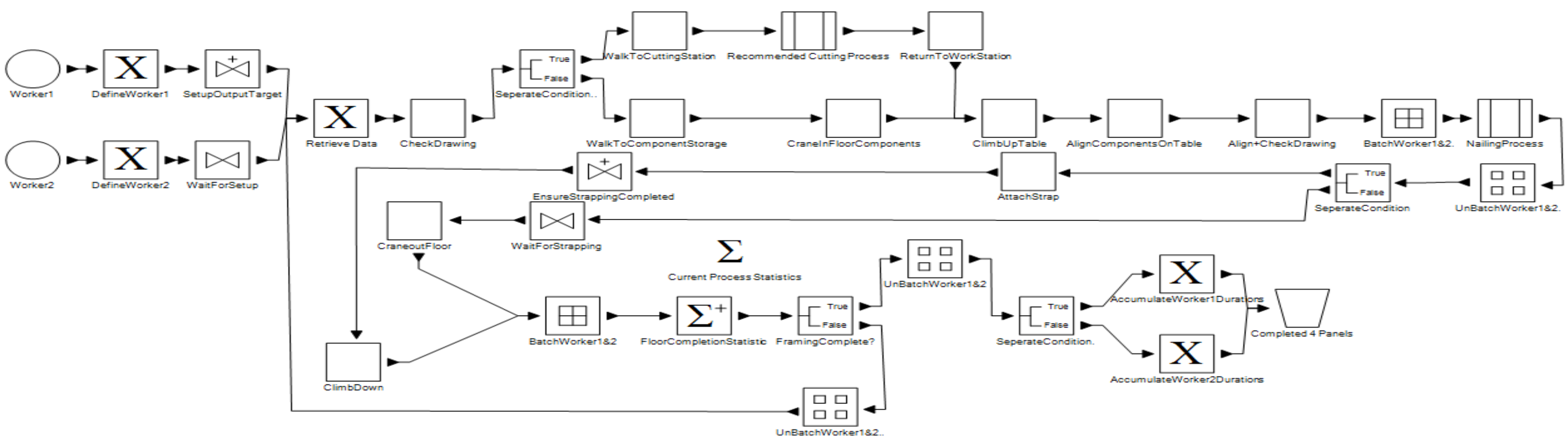


Figure 4.48: Floor framing simulation model with proposed recommendations

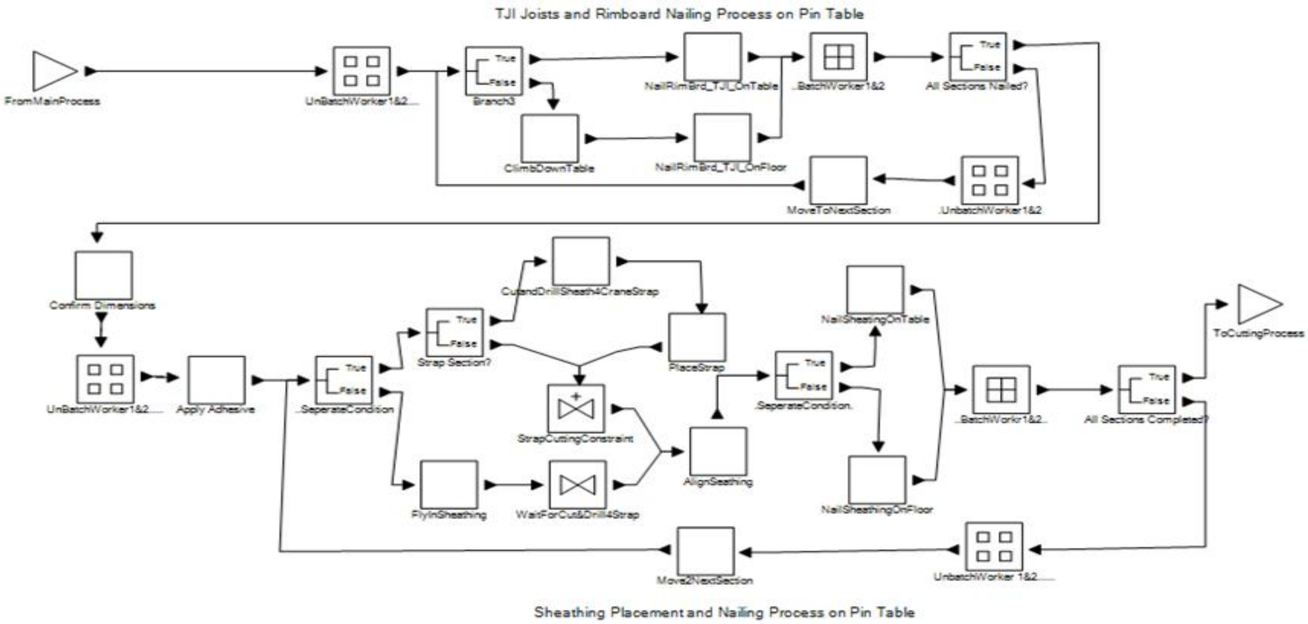


Figure 4.49: Current floor nailing process (simulation model)

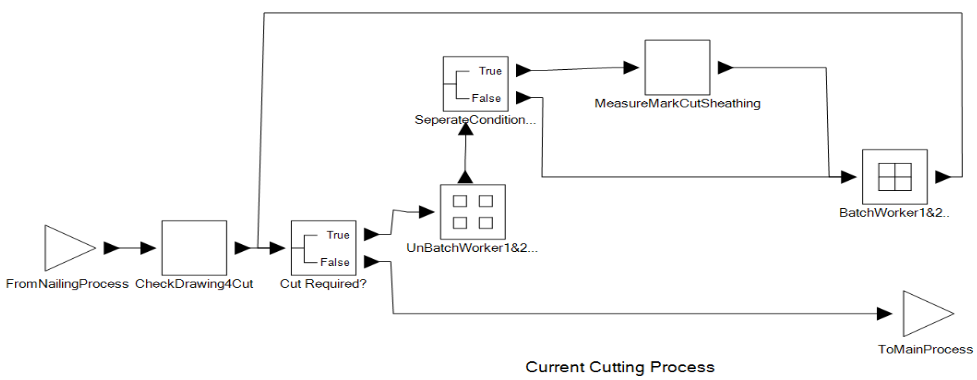


Figure 4.50: Current cutting process (simulation model)

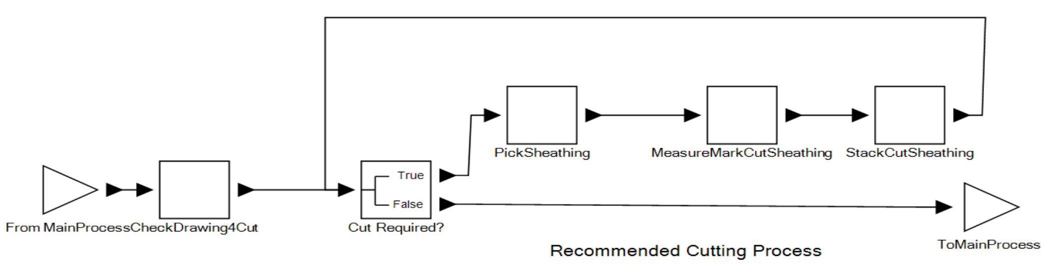


Figure 4.51: Proposed cutting process (simulation model)

This choice was based on only four (4) out of the numerous floor design specifications manufactured in the plant. The adopted design will also reduce/eliminate cutting on the table in squatting and bent postures and reduce/eliminate the time required for cleanup of waste cuttings, thereby providing opportunities for reductions in total task time. Furthermore, the new cutting task (at the cutting station) will reduce Worker 1's idle time (while Worker 2 is craning in the floor components).

Table 4.27: Productivity assessment

FRAMING TASK	Floor Completion Time		Time Saving
	Current	Proposed	
Floor 1	130.70	127.00	3.70
Floor 2	204.99	196.59	8.40
Floor 3	270.15	255.70	14.45
Floor 4	397.70	381.38	16.32

Table 4.28: Postural exposure durations

Adopted Work Postures	Daily Exposure Duration to Awkward Postures (minutes)			
	Current Scenario		Proposed Scenario	
	Worker 1	Worker 2	Worker 1	Worker 2
Upright	123.60	380.33	128.40	381.27
Back 0-20 Flexion	52.00	47.69	52.00	47.78
Back 20-60 Flexion	0.00	0.00	0.00	0.00
Back 60+ Flexion	111.71	0.00	104.22	0.00
Neck 0-20 Flexion	91.60	284.02	91.60	285.06
Neck 20-60 Flexion	138.01	44.00	136.02	44.00
Neck 60+ Flexion	25.70	0.00	20.20	0.00
Legs Straight	164.40	378.02	166.20	379.06
Kneeling/Squatting	106.91	0.00	100.02	0.00

Table 4.29: Ergonomic risk assessment summary

Simulated Scenario	Affected Worker	Posture	Rhs	Total Daily Exposure (mins)	Total Daily Exposure (Hrs)	Md	Mo	Rhs	Rr	Risk Class (Rc)
Current Scenario	Worker 1	BackPosture: ≥ 0 Flexion	3	163.71	2.73	2	1	6	3	Medium
		BackPosture: ≥ 20 Flexion	4	111.71	1.86	1.5	1	6	3	Medium
		NeckPosture: ≥ 0 Flexion	1	255.31	4.26	3	1	3	1	Low
		NeckPosture: ≥ 20 Flexion	2	163.71	2.73	2	1	4	1	Low
		LegPosture: Kneeling/Squatting	4	106.91	1.78	1.5	1	6	3	Medium
	Worker 2	BackPosture: ≥ 0 Flexion	2	47.69	0.79	1	1	2	1	Low
		BackPosture: ≥ 20 Flexion	3	0.00	0.00	0	1	0	1	Low
		NeckPosture: ≥ 0 Flexion	1	328.02	5.47	3	1	3	1	Low
		NeckPosture: ≥ 20 Flexion	2	44.00	0.73	1	1	2	1	Low
		LegPosture: Kneeling/Squatting	4	0.00	0.00	0	1	0	1	Low
Proposed Scenario	Worker 1	BackPosture: ≥ 0 Flexion	3	156.22	2.60	2	0.5	3	1	Low
		BackPosture: ≥ 20 Flexion	4	104.22	1.74	1.5	0.5	3	1	Low
		NeckPosture: ≥ 0 Flexion	1	247.82	4.13	3	0.5	1.5	1	Low
		NeckPosture: ≥ 20 Flexion	2	156.22	2.60	2	0.5	2	1	Low
		LegPosture: Kneeling/Squatting	4	100.02	1.67	1.5	0.5	3	1	Low
	Worker 2	BackPosture: ≥ 0 Flexion	2	47.78	0.80	1	0.5	1	1	Low
		BackPosture: ≥ 20 Flexion	3	0.00	0.00	0	0.5	0	1	Low
		NeckPosture: ≥ 0 Flexion	1	329.06	5.48	3	0.5	1.5	1	Low
		NeckPosture: ≥ 20 Flexion	2	44.00	0.73	1	0.5	1	1	Low
		LegPosture: Kneeling/Squatting	4	0.00	0.00	0	0.5	0	1	Low

Figure 4.52: PSV of proposed station

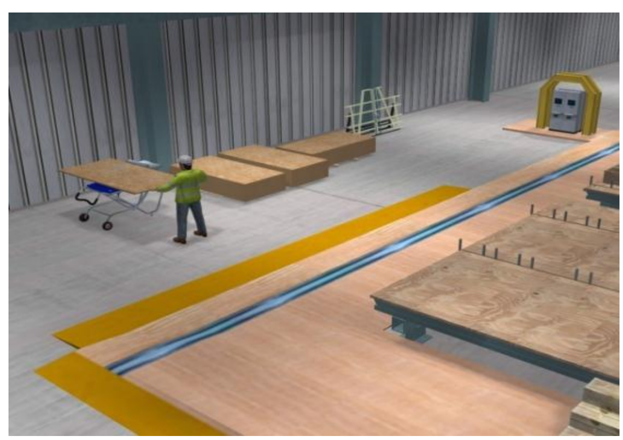


Figure 4.53: PSV of proposed cutting area

A comparison of the current and recommended scenarios shows a total time savings of about 16 minutes for this work process. This productivity increase is due to time saved from the cutting and nailing activities as a result of the recommendations. The ergonomic recommendations have thus helped balance work by reducing idle time. The proposed work conditions also reduce the total durations of awkward postures. The 16-minute time savings allows for better control of the pace of work. This reduces the organizational factor in the ErgoCheck assessment from 2.5 to 2 and changes the risk classification from medium to low risk. There is more potential for productivity increases if optimization is applied towards the pin table redesign. Outputs include (1) a DES model; (2) a productivity assessment (task cycle time); (3) ergonomic risk summary; and (4) post-simulation visualization models.

Conclusion

The presented work shows an application of DES and visualization to assess ergonomic risk and productivity on a residential construction production line. The results obtained show that DES can be used to eliminate the need for repeated site visits and on-site assessments of construction facilities. This reduces the cost and time for assessments and provides alternatives to enhance work planning, design, and redesign aimed at improving productivity (cycle time) and safety and promoting the triple bottom line of social impact (health), environmental impact, and economy.

It should be clarified that the following considerations were taken during database development:

(i) Variability of the working rates was disregarded Deterministic values (mean) of work rate and activity durations were used instead. This is necessary in order to capture the impact of changes for the purpose of comparison.

(ii) It has been assumed that the carpenters consistently follow the logic presented in the simulation.

(iii)Work interruptions, unscheduled breaks, missing components and confusion while reading the specifications and other non-value added activities have not been accounted for.

(iv)Other risk factors (including vibration, environmental risks, and contact stress) have not been assessed within this scope of work.

The success of this application opens a new field for ergonomic assessment by eliminating the dependence on observed data. Also, the simulation model is suitable for use by a process designer in cases where there is limited observation data, since work information can be developed for input to the simulation through the database. There is great flexibility for assessing multiple alternative scenarios since the data for simulation is stored in a database, thus reducing the time and resources needed for developing new simulations for each analysis.

Chapter 5 Summary and Concluding Remarks

5.1 Concluding Remarks

In order to ensure smooth application of ergonomic controls at the workplace, there is a need to identify the factors leading to injury/illness. The importance of identification of ergonomic hazards is connected to the need to eliminate or significantly reduce worker exposure to risk hazards, thus preventing injuries and illnesses by removing their causes. Ergonomic improvements have been shown to have a high impact on reducing injuries and lost time claims (LTCs) and improving overall productivity. It is further noted that knowledge of potential work-related musculoskeletal disorders (WRMSDs) resulting from cumulative exposure to daily construction-related ergonomic risk factors will be strategic towards the implementation of significant corrective measures.

The framework for ergonomic assessment of residential construction tasks has been proposed in order to guide practitioners in executing an assessment both of ergonomics as well as of the impact of the way work is done/designed on productivity. It also provides information useful for selecting the appropriate type of ergonomic analysis based on the several considerations. The developed techniques facilitate the ergonomic analysis process and provide easy-to-use, reliable analysis techniques which are suitable for a wide range of work scenarios. The results from the developed models provide a wide range of information describing risks and potential cumulative health impacts. It should also be pointed out that the cost-benefit implications (learning curve, model cost, and modelling time) of applying the developed techniques are relatively low when compared with common methods.

This research has proposed a systematic framework for ergonomic assessment of residential construction activities. Also, innovative ergonomic quantitative analysis models have been proposed alongside a discrete event simulation (DES) application to serve as decision support for task-based ergonomic analysis of factory-based residential construction processes. An observation-based ergonomic analysis model, ***ErgoCheck***, has also been proposed in this thesis. This model executes a comprehensive body part assessment of ergonomic hazards and provides hazard ratings, classifications, and an exposure-response relationship for each activity and with respect to each body part assessed. This has been found to be very useful in identifying the source and severity of risk, and providing more targeted information for decision making.

A proposed biomechanical analysis model, ***ErgoBioMCheck***, has also been presented in this thesis. This model is suitable for providing quantitative assessments of instantaneous and cumulative lower-back compression and shear stress resulting from dynamic reaction forces during work activities. This model provides easy activity-based assessment, thus making lower-back load analysis easier and faster. It also assesses the cumulative assessment of risk over time, thereby providing potential insight into the occurrence of cumulative trauma disorders (CTDs).

A DES application, ***ErgoSymulate***, has been developed using Simphony's general template linked with a Microsoft Access database engine. This application facilitates the application of event-based simulation in order to assess ergonomic risks. This application raises awareness of the potential of generating ergonomic risk data both of observed and envisioned/designed work tasks from discrete events simulations. His will help in eliminating the dependence on observed data. The simulation model is suitable for use by a process designer if there is only limited observation data, since work information can be developed for input to the simulation through the database. It also offers flexibility for assessing multiple alternative scenarios since the data for simulation is stored in a database. This reduces the need for building new simulations for each analysis.

Finally, a ***fatigue-productivity relationship*** has also been proposed in this thesis, based on the theory of differential muscle fatigue. This relationship has the potential of explaining the onset and behaviour of muscle fatigue and may hold the key to explaining how fatigue affects work productivity. This model requires extensive data collection and is proposed for future work.

These models can be generally applied to any type of work. The overall objective has been to provide solutions which will facilitate proactive ergonomic assessment for new workplace designs ensure easy and comprehensive ergonomic analysis of risks linked to existing work practices, and also serve as decision-making tools leading to the design of safer construction work processes and facilities. Five case studies have been presented in support of the proposed models.

This research has applied scientific principles and practice from (i) occupational safety and health; (ii) health sciences (anatomy, physiology, and epidemiology); (iii) structural engineering (biomechanics, statics, and dynamics); (iv) construction engineering and management (i.e., project management and control, cost, scheduling, absenteeism, planning and design, and work improvement); (v) discrete event and continuous simulation; and (vi) decision support systems (databases, object-oriented modelling).

5.2 Research Limitations and Clarifications

There are several factors and assumptions taken into consideration within this research due to regulations, scope and for simplification purposes. Such include:

Use of Video Recording in ergonomic assessments:

Due to ethical restrictions regarding work with humans and privacy related considerations, the sole source of observed ergonomic risk and productivity data has been from third party data extrapolated from video recordings of actual plan processes have been relied on as a primary source of observed risk and productivity data. The industry partner has been responsible in collecting and processing this information. However, the author was responsible in specifying the data to be collected and made decisions regarding the metrics and variables including the type and precision of outputs desired. These data have been used to assess and validate/verify the models proposed. Third party data collection introduces certain concerns regarding its validity, however, this is not considered by the researcher as impacting on the results of the research based on the nature of information collected. Also, as a secondary data screening, the represented information was verified by another representative of the company. Proposed models have been verified by comparing its results with that of existing state of the art models using the same set of conditions and data, thus data bias becomes insignificant.

Tool-time

Within this thesis, the total cycle time encompasses the sum of the tool-time, exchange time, manual operations and duration of other complementary operator activities. The Tool Time is not given an individual focus within the case studies since the activities assessed are mostly manual operations. However, for tasks involving significant machine operations, the tool-time plays an important role on the physical demand analysis and ergonomic assessment.

Overtime Effect on work and worker productivity

Overtime effect has not been considered in terms of fatigue and productivity. However, this is considered in the assessment of ergonomic risk since duration is a factor which increases the potential of risk. Productivity within this thesis has been limited only to output based on total hours worked. This was necessary to show that applying ergonomic assessments and ergonomic based practices will not increase production time;

instead it holds opportunities of reducing the total time spend on the task to achieve the desired output. The saved time also provided a safety buffer and more rest and recovery time for the worker.

Risk Potential and exposure limits

The hazard potential and exposure limits used within this research are as adopted and recommended by the occupational health and safety association. These are also the same as referenced in ergonomic, medical, biomechanical and other research bodies. .Information pertaining to the genetic differences, fitness levels, recreational activities and medical history of workers are not used in this research to set or limit exposure. The exposure limits are independent of the particular workers involved in this study, however, the statistic used in the development of the experiments in literature and models proposed rely on published national representative population data of 50th percentile of American workers.

5.3 Research Contributions

5.3.1 Development of new ergonomic assessment models

The contributions of this research include the developments of

- a new observation-based ergonomic analysis model (***ErgoCheck***);
- a new biomechanical analysis model (***ErgoBioMCheck***) for cumulative lower-back compression and shear stress analysis;
- a new fatigue-productivity relationship model.

Also, within this research, a discrete event simulation has been applied (***ErgoSymulate***) to model construction tasks and used as a data source for ergonomic risk assessments. This introduces great opportunities for offsite and proactive ergonomic risk assessments.

5.3.2 Contribution to the Academic Body of Knowledge

Application of the methods developed in this research for assessment of ergonomic hazards and design of ergonomic-based work environments is of potential benefit to the academic and research body of knowledge as it increases understanding of factors affecting and relationships among ergonomic hazards. The conclusions drawn within this research adds to existing and future research. The introduction of discrete events modeling as a potential data source also raises possibilities for furthering ergonomics research while also providing flexibilities for data collection.

5.3.3 Contribution to the Construction Industry, Insurance and Occupational Health and Safety

The findings and models developed are of benefit to construction owners and general contractors, insurance agencies and the general public as implementation of proactive ergonomic practices and application of the developed models will leads to increased productivity through reductions in worker injury and its attendant cost, injury-related absenteeism and fatigue. Such a work atmosphere will improve worker morale and industry reputation and consequently productivity. Insurance agencies and the Occupational Health and Safety Act (OHSA) are provided with clear alternative models/techniques for ergonomic risk evaluations which are useful for setting premiums and safety compliance regulations).

5.4 Recommendations for future work

Although this research presents applicable models and techniques for ergonomic analysis of residential construction work, there are, however, further opportunities for ergonomic research and applications within the construction domain. Given the opportunity and resources, the following research areas would be undertaken by the author in the future:

- Validation of the proposed fatigue-productivity relationship model.
- Development of an automated digital human simulation program for ergonomic analysis of workplace design. Such a program would incorporate functionality for cumulative assessment of physiological risks, fatigue, and the productivity status of the simulated scenario.
- Incorporate a cost assessment based on a daily work output and productivity assessment. Cost impacts would be integrated using materials from existing cost estimation programs such as RSMeans Costworks. This would provide an opportunity for assessing the potential short- and long-term cost impact on an overall project.

5.5 Peer Reviewed Publications of this research

- Inyang, N., Al-Hussein, M., El-Rich, M., and Al-Jibouri, S. (2012). "Ergonomic analysis and the need for its integration for planning and assessing construction tasks." *Journal of Construction. Engineering and Management,* posted ahead of print March 23, 2012. doi:10.1061/(ASCE)CO.1943-7862.0000556.

- Inyang, N. and Al-Hussein, M. (2011). "Ergonomic hazard quantification and rating of residential construction tasks." *Proceedings, Canadian Society for Civil Engineering 3rd International/9th Construction Specialty Conference*, (1), 1885-1895.
- Inyang, N., Han, S., Al-Hussein, M., and El-Rich, M. (2012). "A VR model of ergonomics and productivity assessment in panelized construction production line." *Proceedings, Construction Research Congress*, West Lafayette, IN, USA, May 21-23, 1084-1093.

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Appendices

Appendix A: A Sample Physical Demand Analysis

Employer:
Job Title: Meterman/Learner
Dept/Div: Meter Department
Effective Date: 01/01/9_
Location: Toronto, ON
Plant: Downtown
Job Contact:

WORK HOURS/SHIFTS:
The average week is 40 hours, Monday to Friday. Meterman/Learner are assigned to work either one of two shifts, either 8am to 4pm or 8am to 6pm. Two 10-minute breaks and one 20-minute lunch are provided per shift.
JOB PURPOSE:
Learning to clean and change residential and industrial meters.
ESSENTIAL FUNCTIONS:
1. Dissemble and re-assemble meters to clean moving parts using pliers, brush, screwdriver, and air tool.
2. Dissemble damaged meters, current and potential transformers to scrap individual parts using wrench, and screwdriver.
3. Mount current transformer to coil plate using wrench, screwdriver, and power tool.
NON-ESSENTIAL FUNCTIONS:
1. Perform housekeeping duties such as dusting, working with ladders, etc.
2. Transport materials from basement using skid.

GENERAL OBSERVATIONS:
Meterman/Learner will be trained and become qualified in all aspects of shop and field work for approximately 6-8 months. A Meterman/Learner is expected to be able to clean a minimum of 16 meters per shift within 6 months of employment. The work is self-paced, but production volume for the day must be

met. Once every 3-4 weeks, a Meterman/Learner will be expected to work from 8am to 6pm. On that week, the Meterman/Learner will work 4 days per week. Most work areas have good lighting. On days in which work is performed outside, Meterman/Learner will be exposed to a variety of temperatures and weather conditions. These working conditions will vary, depending on the seasonal climate. The most significant physical demand is the potential to handle 100 lb transformers, and frequent standing. On heavy manual material handling tasks, teamwork (2-3 co-workers) will be provided.

Appendix 0-1: PDA sample for material handling task

Manual Material Handling Activities	**Ess. Task 1 (60%/shift)**	**Ess. Task 2 (20%/shift)**	**Ess. Task 3 (5%/shift)**	**Noness. Task 1**	**Noness. Task 2**
Lifting:					
Beginning Heights(in)	6-40"	9-34"	36"	18-20"	30-35"
Ending Heights(in)	6-34"	9-36"	55"	17-20"	71-75"
Weights (lbs)	6-32 lb	6-50 lb	20-80 lb	38-50 lb	20-35 lb
Frequency(#/min)	0.04	0.01	(1-2/month)	Occasional	0.01
Carrying:					
Weight (lbs)	6-32 lb		20-80 lb		34-46"
Distance(in)	960		20-25"		30-40 lb
Frequency(#/min)	0.03		(5-10/month)		(1/day)
Pushing:					
Push Heights(in)		30-33"			34-46"
Horizontal Force(lbs)		45-60 lb			30-40 lb
Frequency(#/min)		(1-2/week)			(1/day)
Pulling:					
Pull Heights(in)		30-33"			
Horizontal Force(lbs)		45-60 lb			
Frequency(#/min)		(12/week)			
Reaching (<10 lb):					
Front Distance(in)	25-28"	25-30"	25-30"		
Vertical Height(in)	9-60"	36"	36"		
Reach Direction	Front	Front	Front		
Frequency(%/shift)	17.9	9.9	1.5		
Handling:					
Weight of Object(lbs)		3-35 lb	6-10 lb		
Grip Force(lbs)	3-8 lb	40-50 lb	30-50 lb		
Diameter(in)	4-7"	2-7"	2-6"		
Frequency(%/shift)	9.8	4.64	1.6		
Fingering:					
Weight of Object(lbs)	4-6 lb	4-6 lb	1-4 lb		
Pinch Force(lb)	6-15 kb		10-15 lb		
Pinch Type	key, 3-pt	key, 3-pt	2 pt		
Finger Flexion (x)			X		
Frequency(%/shift)	32.3	5.5	1.8		

Ess = Essential Task; Noness = Non-essential task

Appendix 0-2: PDA for body posture by type of activity

Activities	Essential task 1: cleaning meters (60%/shift)	Essential task 2: dissemble meters (20%/shift)	Essential task 3: mount CT on coil plate (5%/shift)
Back:			
Straight/neutral	57.1% (Frequent)	12.2% (Occasional)	2.7% (Occasional)
Stoop/flex	2.9% (Occasional)	5.8% (Occasional)	2.2% (Occasional)
Twist/side bend	0% (Never)	1.7% (Occasional)	0% (Never)
Twist & stoop	0% (Never)	0.29% (Occasional)	0% (Never)
Arms:			
Below shoulder	54.8% (Constant)	20% (Occasional)	4.0% (Occasional)
At/above shoulder	5.2% (Occasional)	0% (Never)	0.96% (Occasional)
Overhead	0% (Never)	0% (Never)	0% (Never)
Legs:			
Sitting	36.4% (Frequent)	0% (Never)	0% (Never)
Standing still	21.8% (Occasional)	19.1% (Occasional)	4.3% (Occasional)
Walking	1.7% (Occasional)	0.87% (Occasional)	0.5% (Occasional)
Kneeling	0% (Never)	0% (Never)	0% (Never)
Crouching	0% (Never)	0% (Never)	0.2% (Occasional)
Crawling	0% (Never)	0% (Never)	0% (Never)
Lying	0% (Never)	0% (Never)	0% (Never)

Frequency defined by the Ministry of Labour is 1-33% for Occasional, 34-66% for Frequent, and 67-100% for Constant

“Physical demands analysis.” *Occupational Health Clinics for Ontario Workers Inc*., <http://www.ohcow.on.ca/resources/handbooks/pda/PDA.pdf> (Jun. 25, 2012).

Appendix B: Strength Tables and Model Equations

The following strength tables are from (Mital and Kumar 1998a,b)

Appendix 0-3: Decline in muscular strength capability with age

Age (yr)	Strength exertion capability (%)	
	Men	Women (% of men's capability)
24	100	62
30	97	59
35	94	56
40	91	52
45	89	50
50	83	46
55	80	43
60	75	40
65	71	38

Appendix 0-4: Peak and average isokinetic strengths of females as a percentage of males

Strength	Plane	0.5*R*	0.75*R*	1*R*
Peak	Sagittal	59	61	62
	30° lateral	62	67	63
	60° lateral	62	71	63
Average	Sagittal	60	60	59
	30° lateral	62	65	61
	60° lateral	63	70	56

Note: *R* – Reach.

The table in Appendix 1-4 shows that the isokinetic strength of females is only about 60% of the isokinetic strength of males.

Appendix B2: Isokinetic dynamic lift, back extension, and elbow flexion strength (N)

Appendix 0-5: Isokinetic dynamic lift strength, back extension strength, and elbow flexion strength (N)

Gender	DLS		DBES		DEFS	
	Mean	SD	Mean	SD	Mean	SD
Men	601	100	540	101	324	46
Women	493	139	315	87	196	104

Appendix B3: Mean Peak and Average Isokinetic Lift Strengths (N)

Appendix B3.1 Mean Peak and Average Isokinetic Stoop Lift Strength (N)

Appendix 0-6: Mean peak and average isokinetic stoop lift strength (N)

Strength	Plane	Gender	Stat.	0.5R	0.75R	1R
Peak	Sagittal	Male	x	542	294	233
			SD	215	93	47
		Female	x	296	250	202
			SD	121	104	78
	30° lateral	Male	x	505	299	207
			SD	184	118	72
		Female	x	272	237	162
			SD	122	84	56
	60° lateral	Male	x	334	233	168
			SD	130	82	47
		Female	x	243	174	135
			SD	103	70	39
Average	Sagittal	Male	x	359	192	142
			SD	136	43	36
		Female	x	189	166	134
			SD	84	79	45
	30° lateral	Male	x	328	190	139
			SD	131	60	22
		Female	x	183	159	108
			SD	94	67	35
	60° Lateral	Male	x	205	138	105
			SD	79	37	16
		Female	x	159	109	89
			SD	70	46	24

Appendix B3.2: Mean Peak and Average Isokinetic Squat Lift Strength (N)

Appendix 0-7: Mean peak and average isokinetic squat lift strength (N)

Strength	Plane	Gender	Stat.	0.5R	0.75R	1R
Peak	Sagittal	Male	x	441	320	215
			SD	202	74	33
		Female	x	232	184	155
			SD	91	69	31
	30° lateral	Male	x	416	269	215
			SD	193	77	37
		Female	x	225	176	155
			SD	59	49	23
	60° lateral	Male	x	296	236	182
			SD	76	90	45
		Female	x	186	143	111
			SD	36	43	42
Average	Sagittal	Male	x	273	228	153
			SD	152	54	30
		Female	x	148	125	107
			SD	68	54	34
	30° lateral	Male	x	279	187	154
			SD	161	61	32
		Female	x	145	116	108
			SD	52	39	24
	60° Lateral	Male	x	197	163	120
			SD	53	63	32
		Female	x	121	100	76
			SD	28	37	30

Appendix B4: Pull Strengths (N)

Appendix B4.1: One-handed Isokinetic Pull Strengths (N) in the vertical plane

Appendix 0-8: One-handed isokinetic pull strengths (N) in the vertical plane

Variable	Males		Females	
	Mean	SD	Mean	SD
Speed of exertion (m/s)				
0.30	322	250	61	65
0.35	303	236	60	73
0.48	274	219	51	68
0.58	242	197	49	63
0.75	225	192	48	63
Angle of preferred arm (deg) -30 (arm up and hyperextended; pull down)	173	159	24	6
0 (arm vertical, pull down)	400	265	59	47
30 (pull down)	269	200	43	23
60 (pull down)	220	186	36	21
90 (horizontal pull)	160	165	33	20
120 (pull up)	380	186	30	13
150 (pull up)	370	252	26	10
180 (arm vertical, pull up)	460	273	194	107
210 (pull up, arm hyperextended)	230	152	50	74
240 (pull up, arm hyperextended)	190	195	22	10

Appendix B4.2: Peak and Average Pulling Strength of males in Isometric and Isokinetic modes at low, medium and high heights (N)

Appendix 0-9: Peak and average pulling strength of males in isometric and isokinetic modes at low, medium, and high heights (N)

Mode	Ht	Peak plane						Average plane					
		Sagittal		30° lateral		60° lateral		Sagittal		30° lateral		60° lateral	
		$\bar{x}$	*SD*	$\bar{x}$	*SD*	$\bar{x}$	*SD*	$\bar{x}$	*SD*	$\bar{x}$	*SD*	$\bar{x}$	*SD*
Isom.	Low	423	135	364	71	311	67	292	102	253	47	217	48
	Med.	537	133	432	64	338	65	387	94	300	50	237	50
	High	469	73	428	131	324	139	320	47	277	88	224	107
Isokin.	Low	337	92	326	73	266	31	106	18	93	14	76	10
	Med.	434	96	377	95	289	40	137	25	119	32	86	11
	High	390	88	316	65	235	46	127	30	98	16	75	13

Appendix B4.3: Two-handed Peak and Average Pulling Strength of females in Isometric and Isokinetic modes at low, medium and high heights (N)

Appendix 0-10: Two-handed peak and average pulling strength of females in isometric and isokinetic modes at low, medium, and high heights (N)

Mode	Ht	Peak plane						Average plane					
		Sagittal		30° lateral		60° lateral		Sagittal		30° lateral		60° lateral	
		$\bar{x}$	*SD*	$\bar{x}$	*SD*	$\bar{x}$	*SD*	$\bar{x}$	*SD*	$\bar{x}$	*SD*	$\bar{x}$	*SD*
Isom.	Low	306	80	303	82	247	67	219	63	220	61	176	56
	Med.	385	119	328	84	281	50	275	109	230	72	204	44
	High	368	72	306	92	281	107	267	59	221	75	197	78
Isokin.	Low	209	53	202	46	185	46	64	13	56	9	52	9
	Med.	292	59	268	46	230	42	91	16	78	13	67	13
	High	253	47	218	35	177	30	85	16	74	12	62	13

Appendix B4.4: Two handed Peak and Average Pushing Strength of females in Isometric and Isokinetic modes at low, medium and high heights (N)

Appendix 0-11: Two-handed peak and average pushing strength of females in isometric and isokinetic modes at low, medium, and high heights (N)

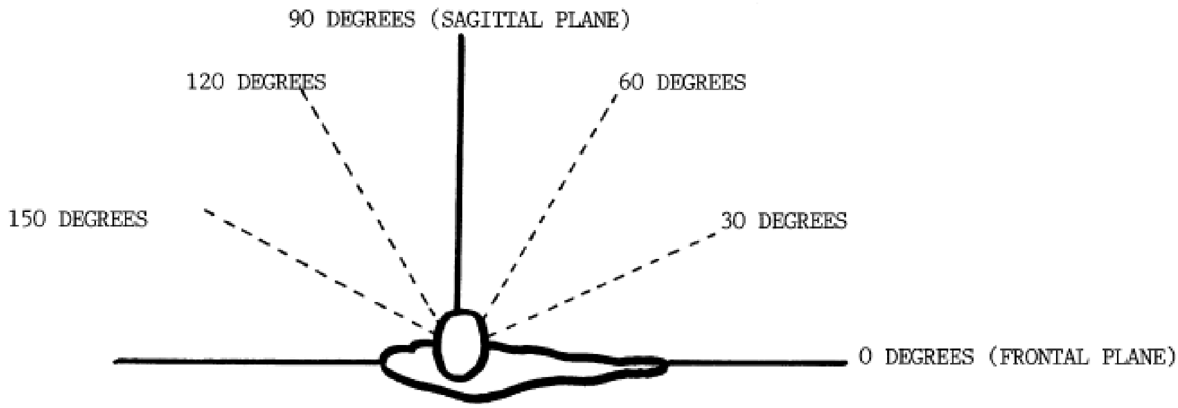
Mode	Ht	Peak plane						Average plane					
		Sagittal		30° lateral		60° lateral		Sagittal		30° lateral		60° lateral	
		$\bar{x}$	*SD*	$\bar{x}$	*SD*	$\bar{x}$	*SD*	$\bar{x}$	*SD*	$\bar{x}$	*SD*	$\bar{x}$	*SD*
Isom.	Low	363	92	335	74	281	59	258	73	233	55	199	47
	Med.	395	123	358	93	295	60	266	85	249	65	202	46
	High	320	44	274	68	229	62	216	74	191	48	156	39
Isokin.	Low	338	96	300	92	253	66	72	43	54	11	47	10
	Med.	339	85	306	76	281	60	60	11	56	9	52	8
	High	327	115	301	104	263	54	58	15	54	13	49	7

Appendix B4: Mean Peak and Average Isokinetic Strength during Arm Lift (N)

Appendix 0-12: Mean peak and average isokinetic strength during arm lift (N)

Strength	Plane	Gender		0.5*R*	0.75*R*	1*R*
Peak	Sagittal	Male	*X*	311	225	162
			SD	87	52	28
		Female	*X*	184	139	101
			SD	39	33	26
	30° lateral	Male	*X*	284	214	156
			SD	69	58	31
		Female	*X*	177	145	98
			SD	44	29	27
	60° lateral	Male	*X*	258	171	129
			SD	69	32	29
		Female	*X*	160	122	81
			SD	40	31	22
Average	Sagittal	Male	*X*	236	180	137
			SD	61	40	24
		Female	*X*	141	109	81
			SD	25	29	22
	30° lateral	Male	*X*	219	174	130
			SD	59	45	28
		Female	*X*	137	114	80
			SD	28	22	24
	60° lateral	Male	*X*	200	140	110
			SD	51	27	30
		Female	*X*	126	98	62
			SD	28	26	19

Note: *R* – Reach.



Appendix 0-13: Arm orientation with respect to the frontal plane

Appendix C: Floor Framing Information and Activity Durations

Appendix C1: Floor Framing Tools, Components and materials

Appendix 0-14: Floor framing tools, components, and materials

Item	Dimensions	Quantity	Density	Weight
Rim-board		3		
TJI Joists		3		
Sheathing		19		
Blocking		18		
Nail Gun		2		
Router		1		
Crane straps		4		
Shop Drawings		1		

Items such as crane straps and shop drawings are of negligible weight.

Appendix C2: Floor Framing Activity Postures

Appendix 0-15: Floor framing activity postures

ID	Unit Activity	NeckPosture	BackPosture	LegPosture
1	NailRimBrd_TJI_OnFloor	Neck 0-20 Flexion	Upright	Legs Straight
2	NailRimBrd_TJI_OnTable	Neck 20-60 Flexion	Back 60+ Flexion	Kneeling/Squatting
3	NailSheating_OnFloor	Neck 0-20 Flexion	Back 0-20 Flexion	Legs Straight
4	NailSheating_OnTable	Neck 20-60 Flexion	Back 60+ Flexion	Kneeling/Squatting
5	FlyInSheathing	Neck 0-20 Flexion	Upright	Legs Straight
6	CraneoutFloor	Neck 0-20 Flexion	Upright	Legs Straight
7	CutDrillSheathTJI4CraneStrap	Neck 60+ Flexion	Back 60+ Flexion	Kneeling/Squatting
8	PlaceStrap	Neck 60+ Flexion	Back 60+ Flexion	Kneeling/Squatting
9	WalkToFromNewCuttingStation	Upright	Upright	Legs Straight
10	MeasureMarkCutSheathingOnFloor	Neck 20-60 Flexion	Back 0-20 Flexion	Legs Straight
11	MeasureMarkCutSheathingOnTable	Neck 60+ Flexion	Back 60+ Flexion	Kneeling/Squatting
12	MeasureMarkCutSheathingAtCuttingStation	Neck 0-20 Flexion	Back 0-20 Flexion	Legs Straight
13	ClimbUpDownTable	Neck 0-20 Flexion	Upright	Legs Straight
14	MoveToNextSection	Neck 0-20 Flexion	Upright	Legs Straight
15	CheckDrawing	Upright	Upright	Legs Straight
16	AttachStrap	Neck 60+ Flexion	Back 60+ Flexion	Legs Straight
17	CleanUp	Neck 20-60 Flexion	Back 60+ Flexion	Legs Straight
18	AlignComponentsOnTable	Neck 20-60 Flexion	Back 0-20 Flexion	Legs Straight
19	CraneInComponents	Upright	Upright	Legs Straight
20	AlignSheathingOnFloor	Neck 0-20 Flexion	Upright	Legs Straight
21	AlignSheathingOnTable	Neck 20-60 Flexion	Back 60+ Flexion	Kneeling/Squatting
22	Align+CheckDrawing	Neck 20-60 Flexion	Back 0-20 Flexion	Legs Straight
23	ApplyAdhesive	Neck 20-60 Flexion	Back 0-20 Flexion	Legs Straight
24	WalkToComponentStorage	Upright	Upright	Legs Straight

25	WalkToCuttingStation	Upright	Upright	Legs Straight
26	PickOrDropSheathing	Neck 20-60 Flexion	Back 60+ Flexion	Legs Straight

Appendix C3: Floor Framing Activity Working Rates

Appendix 0-16: Floor framing activity working rates

ID	Unit Activity	WorkingRate	Description
1	NailingRateSheathing	122	Nails/Minute
2	MeasureMarkCutSheathingOnFloor	0.5	Minutes/Sheathing
3	MeasureMarkCutSheathingOnTable	0.5	Minute/Sheathing
4	MeasureMarkCutSheathingAtCuttingStation	0.5	Minutes/Sheathing
5	CutDrillSheathTJI4CraneStrap	0.5	Minute/ Section
6	NailRimBrd_TJI	5.3	Nails/surface
7	NailSheating	5.7	Nails /surface
8	MoveToNextSection	1	Between adjacent Sections
9	FlyInSheathing	2	Minutes (From Sheathing Storage)
10	CraneInComponents	2.5	Minutes (From Component Storage)
11	ClimbUpDownTable	0.2	Minutes
12	WalkToFromNewCuttingStation	0.5	Minutes
13	PlaceStrap	0.8	Minutes / Section
14	CheckDrawing	2	Minutes
15	AttachStrap	0.5	Minutes
16	CleanUp	0.7	Minutes
17	AlignComponentsOnTable	10	Minutes
18	CraneOutFloor	10	Minutes
19	AlignSheathingOnFloor	0.5	Minutes
20	AlignSheathingOnTable	0.5	Minutes
21	Align+CheckDrawing	1	Minutes
22	ApplyAdhesive	2	Minutes
23	WalkToComponentStorage	2	Minutes
24	WalkToCuttingStation	0.3	Minutes
25	PickOrDropSheathing	0.1	Minutes
26	NailingRateTJI_Rim-board	45	Nails/Minute
27	CarryComponentsToTable	3	Minutes

Appendix C4: Floor Model Framing Requirements

Appendix C4.1: Floor Model 11_150 Framing Requirements

Appendix 0-17: Floor Model 11_150 framing requirements

FloorSection	NailRimBrd_TJI_OnFloor	NailRimBrd_TJI_OnTable	NailSheating_OnFloor	NailSheating_OnTable	CuttingRequired	StrapSection
1	6	7	2	2	No	No
2	7	13	5	1	No	No
3	0	3	0	3	No	Yes
4	2	9	3	1	No	Yes
5	0	3	0	3	No	No
6	2	10	3	1	No	No
7	0	2	0	2	No	No
8	2	10	3	1	No	No
9	0	2	0	2	No	No
10	2	10	3	1	No	No
11	0	0	0	2	No	No
12	2	10	3	1	No	No
13	0	0	0	2	No	Yes
14	2	10	3	1	No	Yes
15	0	0	0	2	No	No
16	2	12	3	1	No	No
17	0	3	0	2	Yes	No
18	2	4	2	1	Yes	No

Appendix C4.2: Floor Model 11_172a Framing Requirements

Appendix 0-18: Floor Model 11_172a framing requirements

FloorSection	NailRimBrd_TJI_OnFloor	NailRimBrd_TJI_OnTable	NailSheating_OnFloor	NailSheating_OnTable	CuttingRequired	StrapSection
1	18	26	5	4	Yes	Yes
2	2	10	2	6	Yes	No
3	2	10	2	6	Yes	No
4	3	15	2.5	5	Yes	Yes
5	2	22	0	2	Yes	No

Appendix C4.3: Floor Model 11_172b Framing Requirements

Appendix 0-19: Floor Model 11_172b framing requirements

FloorSection	NailRimBrd_TJI_OnFloor	NailRimBrd_TJI_OnTable	NailSheating_OnFloor	NailSheating_OnTable	CuttingRequired	StrapSection
1	18	26	5	4	Yes	Yes
2	2	10	2	6	Yes	No
3	2	10	2	6	Yes	No
4	3	15	2.5	5	Yes	Yes
5	2	22	0	2	Yes	No

Appendix C4.4: Floor Model 11_182 Framing Requirements

Appendix 0-20: Floor Model 11_182 framing requirements

FloorSection	NailRimBrd_TJI_OnFloor	NailRimBrd_TJI_OnTable	NailSheating_OnFloor	NailSheating_OnTable	CuttingRequired	StrapSection
1	6	7	1	2	No	No
2	7	13	4	0	No	No
3	0	3	0	2.5	No	Yes
4	2	9	3	0	No	Yes
5	0	3	0	2.5	No	No
6	2	10	3	0	No	No
7	0	2	0	2	No	No
8	2	10	3	0	No	No
9	0	2	0	2	No	No
10	2	10	3	0	No	No
11	0	0	0	2	No	No
12	2	10	3	0	No	No
13	0	0	0	2	No	Yes
14	2	10	3	0	No	Yes
15	0	0	0	2	No	No
16	2	12	3	0	No	No
17	0	3	0	2	Yes	No
18	2	4	1.5	0.5	Yes	No

Appendix C4.5: Floor Model 11_190 Framing Requirements

Appendix 0-21: Floor Model 11_190 framing requirements

FloorSection	NailRimBrd_TJI_OnFloor	NailRimBrd_TJI_OnTable	NailSheating_OnFloor	NailSheating_OnTable	CuttingRequired	StrapSection
1	2	0	0	4	Yes	Yes
2	4	1	3	2	Yes	Yes
3	0	0	0	4	No	No
4	0	0	2	2	No	No
5	5	9	0	6	No	Yes
6	4	11	5	2	Yes	Yes
7	0	9	0	5	Yes	No
8	3	6	0	1	No	No

Appendix C5: Floor Framing Discrete Event activity durations for Model 11_150

Appendix C: 5.1Discrete Event activity durations for Model 11_150 (Worker 1)

Appendix 0-22: Discrete event activity durations for Model 11_150 (Worker 1)

S/n	Unit ActivityName	Activity Location	BackPosture	NeckPosture	Leg Posture	Activity Duration
1	CheckDrawing	Table	Upright	Upright	Straight	2
2	ClimbUpTable	Station	Upright	Neck 0-20 Flexion	Straight	0.2
3	AlignComponentsOnTable	Table	Back 0-20 Flexion	Neck 20-60 Flexion	Straight	10
4	Align+CheckDrawing	Table	Back 0-20 Flexion	Neck 20-60 Flexion	Straight	1
5	NailRimBrd_TJI_OnTable	Table	Back 60+ Flexion	Neck 20-60 Flexion	Squatting	0.8244444
6	MoveToNextSection	Table	Upright	Neck 0-20 Flexion	Straight	1
7	NailRimBrd_TJI_OnTable	Table	Back 60+ Flexion	Neck 20-60 Flexion	Squatting	1.5311111
8	MoveToNextSection	Table	Upright	Neck 0-20 Flexion	Straight	1
9	NailRimBrd_TJI_OnTable	Table	Back 60+ Flexion	Neck 20-60 Flexion	Squatting	0.3533333
10	MoveToNextSection	Table	Upright	Neck 0-20 Flexion	Straight	1
11	NailRimBrd_TJI_OnTable	Table	Back 60+ Flexion	Neck 20-60 Flexion	Squatting	1.06
12	MoveToNextSection	Table	Upright	Neck 0-20 Flexion	Straight	1
13	NailRimBrd_TJI_OnTable	Table	Back 60+ Flexion	Neck 20-60 Flexion	Squatting	0.3533333
14	MoveToNextSection	Table	Upright	Neck 0-20 Flexion	Straight	1
15	NailRimBrd_TJI_OnTable	Table	Back 60+ Flexion	Neck 20-60 Flexion	Squatting	1.1777778
16	MoveToNextSection	Table	Upright	Neck 0-20 Flexion	Straight	1
17	NailRimBrd_TJI_OnTable	Table	Back 60+ Flexion	Neck 20-60 Flexion	Squatting	0.2355556
18	MoveToNextSection	Table	Upright	Neck 0-20 Flexion	Straight	1
19	NailRimBrd_TJI_OnTable	Table	Back 60+ Flexion	Neck 20-60 Flexion	Squatting	1.1777778
20	MoveToNextSection	Table	Upright	Neck 0-20 Flexion	Straight	1
21	NailRimBrd_TJI_OnTable	Table	Back 60+ Flexion	Neck 20-60 Flexion	Squatting	0.2355556
22	MoveToNextSection	Table	Upright	Neck 0-20 Flexion	Straight	1
23	NailRimBrd_TJI_OnTable	Table	Back 60+ Flexion	Neck 20-60 Flexion	Squatting	1.1777778
24	MoveToNextSection	Table	Upright	Neck 0-20 Flexion	Straight	1

25	NailRimBrd_TJI_OnTable	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0
26	MoveToNextSection	Table	Upright		Neck Flexion	0-20	Straight	1
27	NailRimBrd_TJI_OnTable	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	1.1777778
28	MoveToNextSection	Table	Upright		Neck Flexion	0-20	Straight	1
29	NailRimBrd_TJI_OnTable	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0
30	MoveToNextSection	Table	Upright		Neck Flexion	0-20	Straight	1
31	NailRimBrd_TJI_OnTable	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	1.1777778
32	MoveToNextSection	Table	Upright		Neck Flexion	0-20	Straight	1
33	NailRimBrd_TJI_OnTable	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0
34	MoveToNextSection	Table	Upright		Neck Flexion	0-20	Straight	1
35	NailRimBrd_TJI_OnTable	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	1.4133333
36	MoveToNextSection	Table	Upright		Neck Flexion	0-20	Straight	1
37	NailRimBrd_TJI_OnTable	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.3533333
38	MoveToNextSection	Table	Upright		Neck Flexion	0-20	Straight	1
39	NailRimBrd_TJI_OnTable	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.4711111
40	ApplyAdhesive	Table	Back Flexion	0-20	Neck Flexion	20-60	Straight	2
41	AlignSheathing	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.8
42	NailSheating_OnTable	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.0934426
43	MoveToNextSection	Table	Upright		Neck Flexion	0-20	Straight	1
44	AlignSheathing	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.8
45	NailSheating_OnTable	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.0467213
46	MoveToNextSection	Table	Upright		Neck Flexion	0-20	Straight	1
47	CutDrillSheathTJI4CraneStrap	Table	Back Flexion	60+	Neck Flexion	60+	Squatting	0.5
48	PlaceStrap	Table	Back Flexion	60+	Neck Flexion	60+	Squatting	0.8
49	AlignSheathing	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.8
50	NailSheating_OnTable	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.1401639
51	MoveToNextSection	Table	Upright		Neck Flexion	0-20	Straight	1
52	CutDrillSheathTJI4CraneStrap	Table	Back Flexion	60+	Neck Flexion	60+	Squatting	0.5
53	PlaceStrap	Table	Back	60+	Neck	60+	Squatting	0.8

			Flexion		Flexion			
54	AlignSheathing	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.8
55	NailSheating_OnTable	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.0467213
56	MoveToNextSection	Table	Upright		Neck Flexion	0-20	Straight	1
57	AlignSheathing	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.8
58	NailSheating_OnTable	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.1401639
59	MoveToNextSection	Table	Upright		Neck Flexion	0-20	Straight	1
60	AlignSheathing	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.8
61	NailSheating_OnTable	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.0467213
62	MoveToNextSection	Table	Upright		Neck Flexion	0-20	Straight	1
63	AlignSheathing	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.8
64	NailSheating_OnTable	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.0934426
65	MoveToNextSection	Table	Upright		Neck Flexion	0-20	Straight	1
66	AlignSheathing	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.8
67	NailSheating_OnTable	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.0467213
68	MoveToNextSection	Table	Upright		Neck Flexion	0-20	Straight	1
69	AlignSheathing	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.8
70	NailSheating_OnTable	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.0934426
71	MoveToNextSection	Table	Upright		Neck Flexion	0-20	Straight	1
72	AlignSheathing	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.8
73	NailSheating_OnTable	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.0467213
74	MoveToNextSection	Table	Upright		Neck Flexion	0-20	Straight	1
75	AlignSheathing	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.8
76	NailSheating_OnTable	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.0934426
77	MoveToNextSection	Table	Upright		Neck Flexion	0-20	Straight	1
78	AlignSheathing	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.8
79	NailSheating_OnTable	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.0467213
80	MoveToNextSection	Table	Upright		Neck Flexion	0-20	Straight	1
81	CutDrillSheathTJI4CraneStrap	Table	Back Flexion	60+	Neck Flexion	60+	Squatting	0.5

82	PlaceStrap	Table	Back Flexion	60+	Neck Flexion	60+	Squatting	0.8
83	AlignSheathing	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.8
84	NailSheating_OnTable	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.0934426
85	MoveToNextSection	Table	Upright		Neck Flexion	0-20	Straight	1
86	CutDrillSheathTJI4CraneStrap	Table	Back Flexion	60+	Neck Flexion	60+	Squatting	0.5
87	PlaceStrap	Table	Back Flexion	60+	Neck Flexion	60+	Squatting	0.8
88	AlignSheathing	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.8
89	NailSheating_OnTable	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.0467213
90	MoveToNextSection	Table	Upright		Neck Flexion	0-20	Straight	1
91	AlignSheathing	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.8
92	NailSheating_OnTable	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.0934426
93	MoveToNextSection	Table	Upright		Neck Flexion	0-20	Straight	1
94	AlignSheathing	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.8
95	NailSheating_OnTable	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.0467213
96	MoveToNextSection	Table	Upright		Neck Flexion	0-20	Straight	1
97	AlignSheathing	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.8
98	NailSheating_OnTable	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.0934426
99	MoveToNextSection	Table	Upright		Neck Flexion	0-20	Straight	1
100	AlignSheathing	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.8
101	NailSheating_OnTable	Table	Back Flexion	60+	Neck Flexion	20-60	Squatting	0.0467213
102	CheckDrawing	Table	Upright		Upright		Straight	2
103	MeasureMarkCutSheathingOnTable	Table	Back Flexion	60+	Neck Flexion	60+	Squatting	0.5
104	MeasureMarkCutSheathingOnTable	Table	Back Flexion	60+	Neck Flexion	60+	Squatting	0.5
105	MeasureMarkCutSheathingOnTable	Table	Back Flexion	60+	Neck Flexion	60+	Squatting	0.5
106	MeasureMarkCutSheathingOnTable	Table	Back Flexion	60+	Neck Flexion	60+	Squatting	0.5
107	AttachStrap	Table	Back Flexion	60+	Neck Flexion	60+	Straight	0.5
108	ClimbDownTable	Station	Upright		Neck Flexion	0-20	Straight	0.2
109	CleanUp	Floor	Back Flexion	60+	Neck Flexion	20-60	Straight	0.7

Appendix C5.2: Discrete Event activity durations for Model 11_150 (Worker 2)

Appendix 0-23: Discrete event activity durations for Model 11_150 (Worker 2)

S/n	ActivityName	Activity Location	BackPosture	NeckPosture	Leg Posture	Activity Duration
1	CheckDrawing	Table	Upright	Upright	Straight	2
2	WalkToComponentStorage	Floor	Upright	Upright	Straight	8
3	CraneInComponents	Floor	Upright	Upright	Straight	2.5
4	ClimbUpTable	Station	Upright	Neck 0-20 Flexion	Straight	0.2
5	AlignComponentsOnTable	Table	Back 0-20 Flexion	Neck 20-60 Flexion	Straight	10
6	Align+CheckDrawing	Table	Back 0-20 Flexion	Neck 20-60 Flexion	Straight	1
7	ClimbUpTable	Station	Upright	Neck 0-20 Flexion	Straight	0.2
8	NailRimBrd_TJI_OnFloor	Floor	Upright	Neck 0-20 Flexion	Straight	0.7066667
9	MoveToNextSection	Floor	Upright	Neck 0-20 Flexion	Straight	1
10	NailRimBrd_TJI_OnFloor	Floor	Upright	Neck 0-20 Flexion	Straight	0.8244444
11	MoveToNextSection	Floor	Upright	Neck 0-20 Flexion	Straight	1
12	NailRimBrd_TJI_OnFloor	Floor	Upright	Neck 0-20 Flexion	Straight	0
13	MoveToNextSection	Floor	Upright	Neck 0-20 Flexion	Straight	1
14	NailRimBrd_TJI_OnFloor	Floor	Upright	Neck 0-20 Flexion	Straight	0.2355556
15	MoveToNextSection	Floor	Upright	Neck 0-20 Flexion	Straight	1
16	NailRimBrd_TJI_OnFloor	Floor	Upright	Neck 0-20 Flexion	Straight	0
17	MoveToNextSection	Floor	Upright	Neck 0-20 Flexion	Straight	1
18	NailRimBrd_TJI_OnFloor	Floor	Upright	Neck 0-20 Flexion	Straight	0.2355556
19	MoveToNextSection	Floor	Upright	Neck 0-20 Flexion	Straight	1
20	NailRimBrd_TJI_OnFloor	Floor	Upright	Neck 0-20 Flexion	Straight	0
21	MoveToNextSection	Floor	Upright	Neck 0-20 Flexion	Straight	1
22	NailRimBrd_TJI_OnFloor	Floor	Upright	Neck 0-20 Flexion	Straight	0.2355556
23	MoveToNextSection	Floor	Upright	Neck 0-20 Flexion	Straight	1
24	NailRimBrd_TJI_OnFloor	Floor	Upright	Neck 0-20 Flexion	Straight	0
25	MoveToNextSection	Floor	Upright	Neck 0-20 Flexion	Straight	1
26	NailRimBrd_TJI_OnFloor	Floor	Upright	Neck 0-20 Flexion	Straight	0.2355556
27	MoveToNextSection	Floor	Upright	Neck 0-20 Flexion	Straight	1
28	NailRimBrd_TJI_OnFloor	Floor	Upright	Neck 0-20	Straight	0

					Flexion			
29	MoveToNextSection	Floor	Upright		Neck Flexion	0-20	Straight	1
30	NailRimBrd_TJI_OnFloor	Floor	Upright		Neck Flexion	0-20	Straight	0.2355556
31	MoveToNextSection	Floor	Upright		Neck Flexion	0-20	Straight	1
32	NailRimBrd_TJI_OnFloor	Floor	Upright		Neck Flexion	0-20	Straight	0
33	MoveToNextSection	Floor	Upright		Neck Flexion	0-20	Straight	1
34	NailRimBrd_TJI_OnFloor	Floor	Upright		Neck Flexion	0-20	Straight	0.2355556
35	MoveToNextSection	Floor	Upright		Neck Flexion	0-20	Straight	1
36	NailRimBrd_TJI_OnFloor	Floor	Upright		Neck Flexion	0-20	Straight	0
37	MoveToNextSection	Floor	Upright		Neck Flexion	0-20	Straight	1
38	NailRimBrd_TJI_OnFloor	Floor	Upright		Neck Flexion	0-20	Straight	0.2355556
39	MoveToNextSection	Floor	Upright		Neck Flexion	0-20	Straight	1
40	NailRimBrd_TJI_OnFloor	Floor	Upright		Neck Flexion	0-20	Straight	0
41	MoveToNextSection	Floor	Upright		Neck Flexion	0-20	Straight	1
42	NailRimBrd_TJI_OnFloor	Floor	Upright		Neck Flexion	0-20	Straight	0.2355556
43	FlyInSheathing	Floor	Upright		Neck Flexion	0-20	Straight	2
44	AlignSheathing	Floor	Upright		Neck Flexion	0-20	Straight	0.8
45	NailSheating_OnFloor	Floor	Back Flexion	0-20	Neck Flexion	0-20	Straight	0.0934426
46	MoveToNextSection	Floor	Upright		Neck Flexion	0-20	Straight	1
47	FlyInSheathing	Floor	Upright		Neck Flexion	0-20	Straight	2
48	AlignSheathing	Floor	Upright		Neck Flexion	0-20	Straight	0.8
49	NailSheating_OnFloor	Floor	Back Flexion	0-20	Neck Flexion	0-20	Straight	0.2336066
50	MoveToNextSection	Floor	Upright		Neck Flexion	0-20	Straight	1
51	FlyInSheathing	Floor	Upright		Neck Flexion	0-20	Straight	2
52	AlignSheathing	Floor	Upright		Neck Flexion	0-20	Straight	0.8
53	NailSheating_OnFloor	Floor	Back Flexion	0-20	Neck Flexion	0-20	Straight	0
54	MoveToNextSection	Floor	Upright		Neck Flexion	0-20	Straight	1
55	FlyInSheathing	Floor	Upright		Neck Flexion	0-20	Straight	2
56	AlignSheathing	Floor	Upright		Neck Flexion	0-20	Straight	0.8
57	NailSheating_OnFloor	Floor	Back Flexion	0-20	Neck Flexion	0-20	Straight	0.1401639
58	MoveToNextSection	Floor	Upright		Neck	0-20	Straight	1

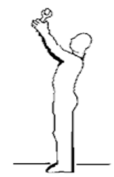
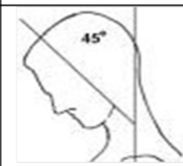
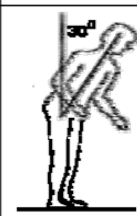
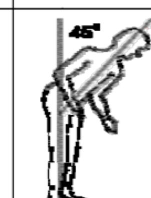
					Flexion			
59	FlyInSheathing	Floor	Upright		Neck Flexion	0-20	Straight	2
60	AlignSheathing	Floor	Upright		Neck Flexion	0-20	Straight	0.8
61	NailSheating_OnFloor	Floor	Back Flexion	0-20	Neck Flexion	0-20	Straight	0
62	MoveToNextSection	Floor	Upright		Neck Flexion	0-20	Straight	1
63	FlyInSheathing	Floor	Upright		Neck Flexion	0-20	Straight	2
64	AlignSheathing	Floor	Upright		Neck Flexion	0-20	Straight	0.8
65	NailSheating_OnFloor	Floor	Back Flexion	0-20	Neck Flexion	0-20	Straight	0.1401639
66	MoveToNextSection	Floor	Upright		Neck Flexion	0-20	Straight	1
67	FlyInSheathing	Floor	Upright		Neck Flexion	0-20	Straight	2
68	AlignSheathing	Floor	Upright		Neck Flexion	0-20	Straight	0.8
69	NailSheating_OnFloor	Floor	Back Flexion	0-20	Neck Flexion	0-20	Straight	0
70	MoveToNextSection	Floor	Upright		Neck Flexion	0-20	Straight	1
71	FlyInSheathing	Floor	Upright		Neck Flexion	0-20	Straight	2
72	AlignSheathing	Floor	Upright		Neck Flexion	0-20	Straight	0.8
73	NailSheating_OnFloor	Floor	Back Flexion	0-20	Neck Flexion	0-20	Straight	0.1401639
74	MoveToNextSection	Floor	Upright		Neck Flexion	0-20	Straight	1
75	FlyInSheathing	Floor	Upright		Neck Flexion	0-20	Straight	2
76	AlignSheathing	Floor	Upright		Neck Flexion	0-20	Straight	0.8
77	NailSheating_OnFloor	Floor	Back Flexion	0-20	Neck Flexion	0-20	Straight	0
78	MoveToNextSection	Floor	Upright		Neck Flexion	0-20	Straight	1
79	FlyInSheathing	Floor	Upright		Neck Flexion	0-20	Straight	2
80	AlignSheathing	Floor	Upright		Neck Flexion	0-20	Straight	0.8
81	NailSheating_OnFloor	Floor	Back Flexion	0-20	Neck Flexion	0-20	Straight	0.1401639
82	MoveToNextSection	Floor	Upright		Neck Flexion	0-20	Straight	1
83	FlyInSheathing	Floor	Upright		Neck Flexion	0-20	Straight	2
84	AlignSheathing	Floor	Upright		Neck Flexion	0-20	Straight	0.8
85	NailSheating_OnFloor	Floor	Back Flexion	0-20	Neck Flexion	0-20	Straight	0
86	MoveToNextSection	Floor	Upright		Neck Flexion	0-20	Straight	1
87	FlyInSheathing	Floor	Upright		Neck Flexion	0-20	Straight	2
88	AlignSheathing	Floor	Upright		Neck	0-20	Straight	0.8

					Flexion			
89	NailSheating_OnFloor	Floor	Back Flexion	0-20	Neck Flexion	0-20	Straight	0.1401639
90	MoveToNextSection	Floor	Upright		Neck Flexion	0-20	Straight	1
91	FlyInSheathing	Floor	Upright		Neck Flexion	0-20	Straight	2
92	AlignSheathing	Floor	Upright		Neck Flexion	0-20	Straight	0.8
93	NailSheating_OnFloor	Floor	Back Flexion	0-20	Neck Flexion	0-20	Straight	0
94	MoveToNextSection	Floor	Upright		Neck Flexion	0-20	Straight	1
95	FlyInSheathing	Floor	Upright		Neck Flexion	0-20	Straight	2
96	AlignSheathing	Floor	Upright		Neck Flexion	0-20	Straight	0.8
97	NailSheating_OnFloor	Floor	Back Flexion	0-20	Neck Flexion	0-20	Straight	0.1401639
98	MoveToNextSection	Floor	Upright		Neck Flexion	0-20	Straight	1
99	FlyInSheathing	Floor	Upright		Neck Flexion	0-20	Straight	2
100	AlignSheathing	Floor	Upright		Neck Flexion	0-20	Straight	0.8
101	NailSheating_OnFloor	Floor	Back Flexion	0-20	Neck Flexion	0-20	Straight	0
102	MoveToNextSection	Floor	Upright		Neck Flexion	0-20	Straight	1
103	FlyInSheathing	Floor	Upright		Neck Flexion	0-20	Straight	2
104	AlignSheathing	Floor	Upright		Neck Flexion	0-20	Straight	0.8
105	NailSheating_OnFloor	Floor	Back Flexion	0-20	Neck Flexion	0-20	Straight	0.1401639
106	MoveToNextSection	Floor	Upright		Neck Flexion	0-20	Straight	1
107	FlyInSheathing	Floor	Upright		Neck Flexion	0-20	Straight	2
108	AlignSheathing	Floor	Upright		Neck Flexion	0-20	Straight	0.8
109	NailSheating_OnFloor	Floor	Back Flexion	0-20	Neck Flexion	0-20	Straight	0
110	MoveToNextSection	Floor	Upright		Neck Flexion	0-20	Straight	1
111	FlyInSheathing	Floor	Upright		Neck Flexion	0-20	Straight	2
112	AlignSheathing	Floor	Upright		Neck Flexion	0-20	Straight	0.8
113	NailSheating_OnFloor	Floor	Back Flexion	0-20	Neck Flexion	0-20	Straight	0.0934426
114	CheckDrawing	Floor	Upright		Upright		Straight	2
115	CraneoutFloor	Floor	Upright		Neck Flexion	0-20	Straight	10

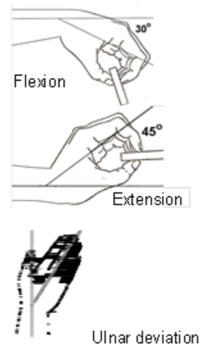
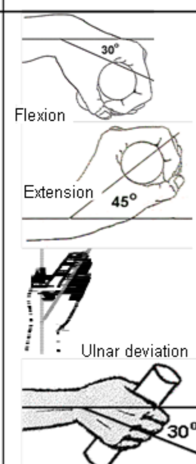
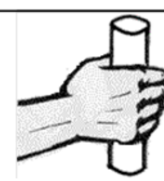
Appendix D: Ergonomics Task Analysis Worksheets

Appendix D1: Task Analysis Checklist

Appendix 0-24: WAC 296-62-05174 Appendix B: Criteria for analyzing and reducing WMSD hazards for employers who choose the Specific Performance Approach.

Awkward Posture				Check (✓) here if this is a WMSD hazard
Body Part	**Physical Risk Factor**	**Duration**	**Visual Aid**	
Shoulders	Working with the hand(s) above the head or the elbow(s) above the shoulder(s)	More than 4 hours total per day		❑
	Repetitively raising the hand(s) above the head or the elbow(s) above the shoulder(s) more than once per minute	More than 4 hours total per day		❑
Neck	Working with the neck bent more than 45º (without support or the ability to vary posture)	More than 4 hours total per day		❑
Back	Working with the back bent forward more than 30º (without support, or the ability to vary posture)	More than 4 hours total per day		❑
	Working with the back bent forward more than 45º (without support or the ability to vary posture)	More than 2 hours total per day		❑
Knees	Squatting	More than 4 hours total per day		❑
	Kneeling	More than 4 hours total per day		❑ ❑

High Hand Force

Body Part	Physical Risk Factor	Combined with	Duration	Visual Aid	Check (✓) here if this is a WMSD hazard
Arms, wrists, hands	Pinching an unsupported object(s) weighing 2 or more pounds per hand, or pinching with a force of 4 or more pounds per hand (comparable to pinching half a ream of paper)	Highly repetitive motion	More than 3 hours total per day		❑
		Wrists bent in flexion 30° or more, or in extension 45° or more, or in ulnar deviation 30° or more	More than 3 hours total per day		❑
		No other risk factors	More than 4 hours total per day		❑
Arms, wrists, hands	Gripping an unsupported object(s) weighing 10 or more pounds per hand, or gripping with a force of 10 pounds or more per hand (comparable to clamping light duty automotive jumper cables onto a battery)	Highly repetitive motion	More than 3 hours total per day		❑
		Wrists bent in flexion 30° or more, or in extension 45° or more, or in ulnar deviation 30° or more	More than 3 hours total per day		❑
		No other risk factors	More than 4 hours total per day		❑

Highly Repetitive Motion				Check (✓) here if this is a WMSD hazard
Body Part	**Physical Risk Factor**	**Combined with**	**Duration**	
Neck, shoulders, elbows, wrists, hands	Using the same motion with little or no variation every few seconds (excluding keying activities)	No other risk factors	More than 6 hours total per day	❑
	Using the same motion with little or no variation every few seconds (excluding keying activities)	Wrists bent in flexion 30° or more, or in extension 45° or more, or in ulnar deviation 30° or more **AND** High, forceful exertions with the hand(s)	More than 2 hours total per day	❑
	Intensive keying	Awkward posture, including wrists bent in flexion 30° or more, or in extension 45° or more, or in ulnar deviation 30° or more	More than 4 hours total per day	❑
		No other risk factors	More than 7 hours total per day	❑

Repeated Impact				Check (✓) here if this is a WMSD hazard
Body Part	**Physical Risk Factor**	**Duration**	**Visual Aid**	
Hands	Using the hand (heel/base of palm) as a hammer more than once per minute	More than 2 hours total per day		❑
Knees	Using the knee as a hammer more than once per minute	More than 2 hours total per day		❑

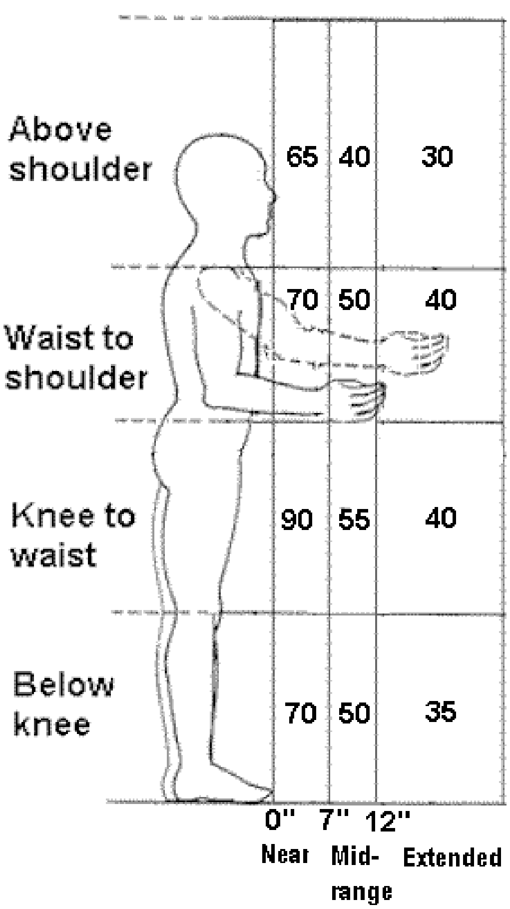
For each "caution zone job," find any physical risk factors that apply. Reading across the page, determine if all of the conditions are present in the work activities. If they are, a WRMSD hazard exists and must be reduced below the hazard level or to the degree technologically and economically feasible (see WAC 296-62-05130(4), specific performance approach).

This analysis only pertains if you have "caution zone jobs" where employees lift 10 lbs. or more (see WAC 296-62-05105, Heavy, Frequent, or Awkward Lifting) and you have chosen the specific performance approach.

Step 1 **Find out the actual weight of objects that the employee lifts.**

Actual Weight = ________lbs.

Step 2 **Determine the Unadjusted Weight Limit.** Where are the employee's hands when they begin to lift or lower the object? Mark that spot on the diagram below. The number in that box is the Unadjusted Weight Limit in pounds.



Unadjusted Weight Limit: _________ lbs.

Step 3 **Find the Limit Reduction Modifier.** Find out how many times the employee lifts per minute and the total number of hours per day spent lifting. Use this information to look up the Limit Reduction Modifier in the table below.

How many lifts per minute?	**For how many hours per day?** 1 hr or less	1 hr to 2 hrs	2 hrs or more
1 lift every 2-5 mins.	1.0	0.95	0.85
1 lift every min	0.95	0.9	0.75
2-3 lifts every min	0.9	0.85	0.65
4-5 lifts every min	0.85	0.7	0.45
6-7 lifts every min	0.75	0.5	0.25
8-9 lifts every min	0.6	0.35	0.15
10+ lifts every min	0.3	0.2	0.0

Note: For lifting done less than once every five minutes, use 1.0

Limit Reduction Modifier: _____.______

Step 4 **Calculate the Weight Limit.** Start by copying the Unadjusted Weight Limit from Step 2.

Unadjusted Weight Limit: = ______ lbs.

If the employee twists more than 45 degrees while lifting, reduce the Unadjusted Weight Limit by multiplying by 0.85. Otherwise, use the Unadjusted Weight Limit

Twisting Adjustment: = _______.____

Adjusted Weight Limit: = ______ lbs.

Multiply the Adjusted Weight Limit by the Limit Reduction Modifier from Step 3 to get the Weight Limit. **X**

Limit Reduction Modifier: _______.___

Weight Limit: = ______lbs.

Step 5 **Is this a hazard?** Compare the Weight Limit calculated in Step 4 with the Actual Weight lifted from Step 1. If the Actual Weight lifted is greater than the Weight Limit calculated, then the lifting is a WMSD hazard and must be reduced below the hazard level or to the degree technologically and economically feasible.

Note: If the job involves lifts of objects with a number of different weights and/or from a number of different locations, use Steps 1 through 5 above to:

1. Analyze the two worst case lifts -- the heaviest object lifted and the lift done in the most awkward posture.
2. Analyze the most commonly performed lift. In Step 3, use the frequency and duration for <u>all</u> of the lifting done in a typical workday.

Use the instructions below to determine if a hand-arm vibration hazard exists.

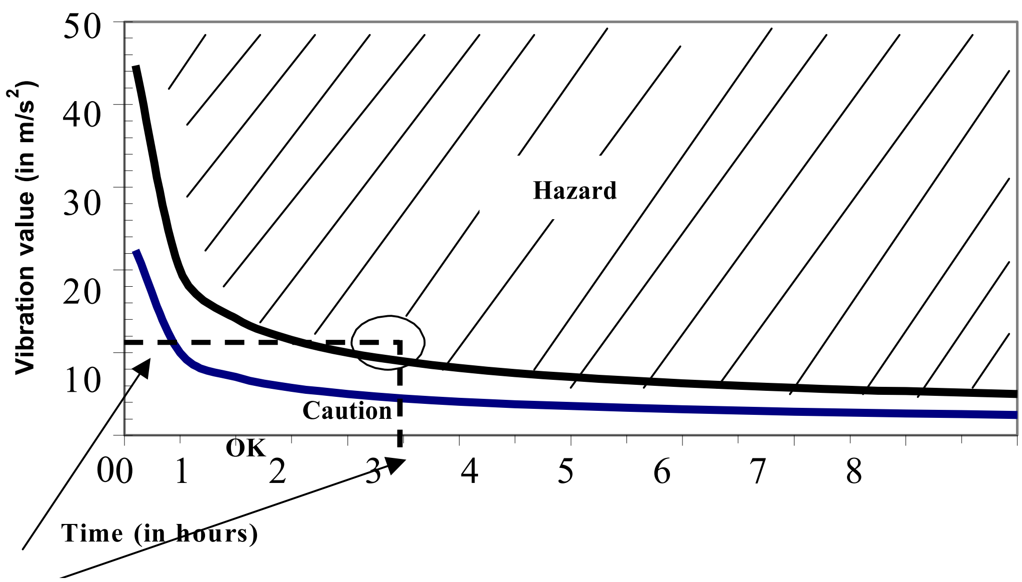
Step 1. Find the vibration value for the tool. (Get it from the manufacturer, look it up at this web site: http://umetech.niwl.se/vibration/HAVHome.html, or you may measure the vibration yourself). The vibration value will be in units of meters per second squared (m/s^2). On the graph below find the point on the left side that is equal to the vibration value.

Note: You can also link to this web site through the L&I WISHA Services Ergonomics web site: http://www.lni.wa.gov/wisha/ergo

Step 2. Find out how many total hours per day the employee is using the tool and find that point on the bottom of the graph.

Step 3. Trace a line in from each of these two points until they cross.

Step 4. If that point lies in the crosshatched "Hazard" area above the upper curve, then the vibration hazard must be reduced below the hazard level or to the degree technologically and economically feasible. If the point lies between the two curves in the "Caution" area, then the job remains as a "Caution Zone Job." If it falls in
the "OK" area below the bottom curve, then no further steps are required.



Example:
An impact wrench with a vibration value of **12 m/s²** is used for **2½ hours** total per day. The exposure level is in the Hazard area. The vibration must be reduced below the hazard level or to the degree technologically and economically feasible.

Note: The caution limit curve (bottom) is based on an 8-hour energy-equivalent frequency-weighted acceleration value of 2.5 m/s^2. The hazard limit curve (top) is based on an 8-hour energy-equivalent frequency-weighted acceleration value of 5 m/s^2.