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Ergonomics, loss management and surveillance: biomechanical, psychophysical and physiological loads and industrial handwheel actuation

By

©

Tyler Amell

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled *Ergonomics, loss management and surveillance in a mid-sized industrial organization: biomechanical, psychophysical and physiological loads and industrial handwheel actuation* submitted by *Tyler Amell* in partial fulfillment of the requirements for the degree of *Doctor of Philosophy* in Rehabilitation Science.

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DEDICATION

This body of research is dedicated to all those workers who have needlessly suffered an injury or illness while on the job. From their afflictions, I hope that someday we will learn to control and prevent the incidents in such a manner that one day such a body of work will not be necessary.

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ABSTRACT

The impact of occupational injury upon industry is profound, particularly with respect to afflictions involving the musculoskeletal system. This thesis describes how ergonomics, surveillance and loss management fit together in a seamless system targeted at controlling and preventing these afflictions. It contains several new discoveries concerning the ability of a worker to operate an industrial handwheel. We revealed that currently existing standards for the design of this task are insufficient.

The analysis of workers in the field revealed that the flexor carpis radialis, and erector spinae muscles were very active. A series of laboratory experiments were undertaken to determine the effect of trunk posture, upper extremity position, handwheel height above grade, distance and contour of foot support, and pitch angle orientation upon maximal strength, electromyographic activity (EMG), perceived exertion, oxygen consumption and heart rate. Upper extremity adduction strength and EMG was not affected by axial trunk rotation; however, upper extremity position did affect these variables. Maximal voluntary two-handed counter-clockwise net tangential static force was found to be below those forces required to actuate handwheels in the field. Hence, it is not surprising that overexertion injuries are commonly observed. To control for these types of injuries, the static force demands of the task should reside well below 700 N.

Handwheel pitch angle and height above the grade significantly affected the compression as well as shear forces acting upon the low back, exceeding their tolerance. As high as 99% of the referent population is incapable of generating sufficient upper extremity strength to safely complete the task. Both static and dynamic handwheel

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operation was studied using psychophysical methods. It was revealed that a handwheel height of 93 cm induced the least amount of perceived exertion during both actuation and operation. The physiological experiments revealed the task to be very heavy work, based upon observed levels of oxygen consumption and heart rate. The results indicate that the task imparts a great psychophysical and physiological load on the worker and that these factors must be considered in the design of such control devices in an effort to optimize the fit between this task and the worker.

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Chapter 1

General Introduction[1]

[1] A portion of this chapter has been published. AMELL, T.K. & KUMAR, S. (2001). Work-related Musculoskeletal Disorders: Design as a Prevention Strategy. A Review. *Journal of Occupational Rehabilitation*. 11(4), 255-265.

1.1 Introduction

Work-related musculoskeletal disorders affect a large number of workers every year (Praemer *et al.*, 1992). In 1999, 35,440 incidents were reported in the Canadian Province of Alberta that required recuperation away from work. Incidents of the sprain, strain and tear nature of injury accounted for 44.4% of this total while overexertion and repetitive motion was noted as the type of precipitating event in 29.5% of all cases (Alberta Human Resources and Employment, 2000). The number of repetitive motion incidents increased 58% over 1998 values and contributed to 3.3% of all incidents. All compensable musculoskeletal injuries and illnesses combined cost over $90 million (Alberta Human Resources and Employment, 2000). This value contributed significantly to the total cost of compensable claims in the province in 1999 (Workers' Compensation Board of Alberta, 2000). The costs incurred in 1999 were 45% over-budget and 75% over the total claim costs for the calendar year 1997 (Workers' Compensation Board of Alberta, 2000 & 1999). Similarly, on a national scale, there were 793,666 reported incidents in Canada during the 1998 calendar year (HRDC 2000). Of these, 375,360 were compensable, 151,581 (41%) of which were sprain and strain lost-time claim incidents (HRDC 2000). Bodily motion was the source of claim in 65,405 (17%) cases while overexertion was noted as the event in 91,653 (26%) cases. In the United States, similar trends and costs have been reported. For example, low back pain is one of the most common conditions afflicting the musculoskeletal system, and in 1991 the total cost for compensation, lost time at work and treatment was estimated to be approximately $72 Billion, $24 Billion of which was spent on treatment alone (Deyo *et al.*, 1991).

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The aforementioned costs and number of injuries serve only as estimates of the true cost and nature of work-related musculoskeletal disorders because compensable claims are typically limited to the most severe incidents and as a result only account for a portion of the true total number of musculoskeletal disorders (Pransky *et al.*, 1999; Courtney *et al.*, 1997; Sorock *et al.*, 1993; Wigglesworth *et al.*, 1990). Thus, it may be that the majority of incidents of work-related musculoskeletal disorders are not reported for a variety of reasons and hence the problem may be larger than official figures indicate (Rosenman *et al.*, 2000; Biddle *et al.*, 1998).

In addition to the claim costs, there are also numerous other costs that contribute to the economic burden of work-related musculoskeletal disorders such as direct medical, indemnity and risk management costs, lost productivity, overtime associated with compensating for injured workers, work-site modification and/or supervision of injured workers, recruitment and retraining of replacement workers, human resources department costs for managing injuries and unfortunately, under certain circumstances, legal fees (Riihimäki, 1995; Cockburn *et al.*, 1999; Burton *et al.*, 1999; Feuerstein *et al.*, 1999). Other factors include the emotional, psychological and financial burden placed upon the family and extended family of the affected worker. Thus, it is difficult to ascertain the exact economic impact that these incidents have upon industry, however in light of the aforementioned values, it must be large. Regardless of the actual costs of these incidents, work-related musculoskeletal disorders represent a significant opportunity for cost reduction since these incidents are controllable and in certain instances may be preventable (Moore, 1997; Volinn, 1999; Melhorn *et al.*, 1999; Lincoln *et al.*, 2000; Bernacki *et al.*, 1999; Brisson *et al.*, 1999). Furthermore, since costs continue to rise, current initiatives aimed at controlling work-related musculoskeletal disorders are not succeeding (Workers' Compensation Board of Alberta, 2000 & 1999). In addition to these cost factors, there is also a moral and legal obligation on behalf of the industry to maintain the health of its' workforce.

One method shown to be of utility in efforts to manage work-related musculoskeletal disorders is ergonomics (United States General Accounting Office, 1997). In a 1997 report to the United States Congress, the General Accounting Office determined that ergonomic programs yielded positive benefits such as a reduction in

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workers' compensation costs associated with musculoskeletal disorders in addition to reductions in overall occupational injuries and illnesses as well as the duration of lost-time. Similar conclusions were reached by researchers and focus groups at the National Institute for Occupational Safety and Health (NIOSH, 1997) as well as the National Research Council (NRC, 1999 & 1998). As a result of reports such as these, governing bodies are currently in the process of integrating ergonomics into occupational safety and health acts in Canada.

The purpose of this chapter is to review the concept of work-related musculoskeletal disorders and discuss the basis of their prevention as a primary means of occupational injury and illness control. The principal contributory role of ergonomics/human factors is presented as a viable means of control and prevention and an important contributor to the comprehensive management of these disorders.

1.1.1 Work-Related Musculoskeletal Disorders

Work-related musculoskeletal disorders are frequently referred to by many synonyms including occupational musculoskeletal injuries and illnesses, the preferred term for some collective insurance agencies (Workers' Compensation Board of Alberta, 2000), as well as work-related musculoskeletal disorders of the upper extremity, and repetitive strain/stress injuries. The term disorder is sometimes preferred due to the multifactorial nature of the problem, acknowledging the various physical, psychological, psychosocial and organizational risk factors and not limiting itself to the terms 'injury' or 'illness' (WHO, 1985). All of these terms refer to same basic family of disorders affecting the tissues of the musculoskeletal system (tendons, muscles, ligaments, bones, nerves and vascular structures) and are usually limited to the upper extremity and low back (NRC, 1998; WHO, 1985; Putz-Anderson, 1988; Hagberg *et al.*, 1995; Moon & Sauter, 1996). Factors contributing to the onset of work-related musculoskeletal disorders include physical, physiological as well as psychological components in addition to sociological and organizational components (Hagberg *et al.*, 1995; Moon & Sauter, 1996).

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Physical etiological factors contributing to tendon disorders include reduced lubrication between tendons and tendon sheaths as a result of excess relative movement (tenosynovitis) as well as high peak loads and cumulative strain (tendonitis) (Moore *et al.*, 1990; Rowe, 1987; Wells & Keir 1999). Etiological factors contributing to nerve disorders include injury to the nerve due to increased hydrostatic pressures in the carpal canal, direct contact stress on the nerve by overlying tendon(s) (carpal tunnel syndrome) or impingement (thoracic outlet syndrome) as well as stretch (Wells & Keir, 1999; Wall *et al.*, 1992). In general, factors known or thought to contribute to the development of upper limb disorders are broadly categorized by Muggleton *et al.*, (1999) as load related (including vibration), posture related (including repetitiveness) and environmental. Load related risk factors include vibration, mechanical shocks, palmar and gripping loads as well as hard/sharp edges which focus contact forces. Posture related risk factors include excessive wrist flexion/extension and ulnar/radial deviation as well as the repetitive nature of movements about the elbow and shoulder and the respective exposure time. Environmental risk factors listed by Muggleton *et al.*, (1999) include temperature, humidity and psychological stress. With respect to the low back, risk factors have been reported from both individual and occupational perspectives. Individual risk factors include among others age, genetics, smoking, muscular strength and physical fitness etc. while occupational factors include heavy physical work, overexertion, static postures, frequent bending and twisting, lifting and forceful movements etc (Kumar, 2001; Marras, 2000; Clemmer *et al.*, 1991; Clemmer & Mohr, 1991; Hoogendoorn *et al.*, 1999; Frank *et al.*, 1996a & b; Holmstrom *et al.*, 1992a & b; Marras *et al.*, 1995; Burdof & Sorock 1997; Keyserling 2000a & b). Several theories have been put forth to explain work-related musculoskeletal disorders; among these are the multivariate interaction theory whereby genetic, morphological, psychosocial and biomechanical factors combine to contribute to the disorder (Kumar, 2001). The differential fatigue theory involves muscles reaching a fatigued state at different times during a work shift and hence causing stresses to concentrate upon muscles that may not be the most suitable to perform the task (Kumar, 2001). Cumulative load is another theory that addresses the lifetime exposure to mechanical loading in the low back and alters (reduces) the point at which failure

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tolerance is reached hence causing injury (Kumar, 2001). Overexertion theory involves excessive exertions beyond the physical tolerance limits of the system (Kumar, 2001).

General factors that have been described as necessary for the development of a work-related musculoskeletal disorder include: insufficient recovery time following task completion, high task repetition, as well as awkward posture and high force requirements of a task (Silverstein *et al.*, 1996 & 1986; Putz-Anderson, 1988). In addition to these physical (mechanical) factors, psychosocial factors such as stress as well as social, organizational and behavioural factors also contribute to the risk of work-related musculoskeletal disorder development (Moon & Sauter, 1996). It is apparent that there are a multitude of factors that must be considered and accounted for in any research related to work-related musculoskeletal disorders (NIOSH, 1997; NRC, 1999). However, it can be safely stated that when these factors are combined in varying proportions, there is sufficient risk of disorder development (Putz-Anderson, 1988; Muggleton *et al.*, 1999; Silverstien & Fine 1991; Keyserling, 2000a & b).

Unfortunately there is wide variation in the focus and quality of scientific literature concerning work-related musculoskeletal disorders (Silverstein *et al.*, 1986, Armstrong, 1986; Armstrong *et al.*, 1987; Rempel *et al.*, 1992; Stock *et al.*, 1991). According to Muggleton *et al.* (1999), this is due to ethical considerations precluding cause and effect studies into the development of work-related musculoskeletal disorders. As a result, there is a wealth of information in the form of workplace surveys, case studies, physiological and mathematical modeling, as well as anecdotal evidence supporting risk factors for the development of work-related musculoskeletal disorders. Viikari-Juntura (1997) states that well-designed epidemiological studies defining dose-response relationships relating to the development of work-related musculoskeletal disorders is sparse at present.

One critical review by the National Research Council (1998) in the United States attempted to address this concern and evaluated diverse research articles against a set of criteria to determine causality. Some examples of the criteria included temporal ordering of effects, cause and effect covary and the absence of other plausible explanations for the observed effect. The outcome of this review concluded that, among other things, "there is a strong biological plausibility to the relationship between the incidence of

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musculoskeletal disorders and the causative exposure factors in high-exposure occupational settings" (NRC, 1998; Kumar, 1990). Furthermore, the authors conclude "research clearly demonstrates that specific interventions can reduce the reported rate of musculoskeletal disorders for workers who perform high-risk tasks."

1.1.2 Control and Prevention Strategies

Despite the acknowledged importance of injury and illness prevention at the national and international level (Nelson, 1987; Romer, 1987; NIOSH, 1993, 1996 & 1999), efforts have been slow to yield results at the plant and organizational level. One factor contributing significantly to this issue is that the role of preventive medicine in addressing work-related musculoskeletal disorder concerns is underutilized (Hensrud, 2000a, b & c). Hensrud (2000a) attributes this underutilization to several factors including a fundamental limitation in the traditional disease/treatment model of medical practice. Although the predominant method of choice for many acute conditions not related to the musculoskeletal system, the traditional disease/treatment model does not utilize preventive measures to their maximum potential for reasons such as lack of physician knowledge, patient ignorance of benefits and lack of preventive service systems (2000a). Furthermore, it has been suggested that primary care physicians should play a more active role in the secondary prevention of work-related musculoskeletal disorder management in support of primary and tertiary prevention efforts. This is due to the fact that they are in a unique position because they are frequently sought for medical treatment early on in the musculoskeletal disorder process (Viikari-Juntura & Riihimaki, 1999).

Three modes of prevention are typically described in the literature (Hensrud, 2000a; Baker & Matte, 1992). Together, these modes are concerned with the reduction of risk factors that result in injury and illness as well as the maintenance and promotion of health (Hensrud, 2000a). The goal of *primary prevention* is that the injury or illness does not occur; an example of primary prevention relevant to work-related musculoskeletal disorders would be the use of alternative hand tools with vibration damping features. The goal of *secondary prevention* is the early detection and treatment of asymptomatic injury

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or illness before symptoms occur. Secondary prevention relies extensively on occupational injury and illness surveillance (Baker & Matte, 1992). The goal of *tertiary prevention* is that the consequence of an existing injury or illness does not occur or that an existing injury or illness does not recur. A pertinent example of tertiary prevention would be the introduction of mechanical lifting aids in manual materials handling tasks such that the biomechanical load and related risk of low back injury is greatly diminished after workers have come forward with symptoms.

A focus on preventive measures in occupational musculoskeletal injury and illness control and management programs at the plant and organizational level of industry is the most appropriate method of addressing these concerns. Ergonomics and human factors principles may be employed in two of the three aforementioned levels of preventive action. Their inherent focus on design serves as a sound basis from which comprehensive injury management programs may be based. Such a system would provide a basis, such that the multifactorial and complex nature of occupational musculoskeletal injuries and illnesses could be addressed from psychosocial work organizational platforms in addition to the cognitive, physiological and biomechanical platforms inherent to the design.

1.1.3 Design as a Control and Prevention Strategy

Although theoretically and practically it is impossible to prevent all injuries and illnesses from occurring, due to the fact that zero-risk can never be achieved (Kumar, 1994), a significant reduction in disabling injuries and illnesses is attainable, and all other incidents can be managed through a comprehensive, multifaceted approach. This holds particularly true for work-related musculoskeletal disorders. It has been shown that multidisciplinary programs consisting of input from individuals with specialization in ergonomics and human factors, organizational psychology, occupational medicine, engineering, health and safety, management and workers have had the greatest impact on managing and controling work-related musculoskeletal disorders (Moore, 1997; Volinn, 1999; Melhorn *et al.*, 1999; Lincoln *et al.*, 2000; Bernacki *et al.*, 1999; Brisson *et al.*, 1999; Drury *et al.*, 1999; Feuerstein *et al.*, 2000; Amik *et al.*, 2000).

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Ergonomics and human factors design principles may be employed as both primary and tertiary prevention strategies, with particular emphasis on the former. Ergonomics and human factors employ the optimal design of workspaces, tools, equipment, environment and products with respect to safety and efficiency of usage. In order to implement these principles into prevention efforts, sound knowledge of the physical and psychosocial risk factors should be incorporated into the design (Keyserling 2000a & b; Dasinger *et al.*, 2000; Carayon *et al.*, 1999; Ayoub 1990a, b & c). One method of obtaining this information is through the systematic review process as well as the process undertaken by government organized research focus groups in the United States (NIOSH, 1997, NRC, 1998 & 1999, Rosenstock & Thacker, 2000). With knowledge of the physical and physiological limitations of the worker, as well as the organizational environment, the so-called corporate culture, the design principles may be employed during the planning and construction of the work-space, equipment or job task as a means of primary prevention. Such significant front-end thought, input and planning into designing for the worker is desired. If properly implemented, this process should substantially reduce the future risk of injury or illness when the work-space or equipment becomes operational, or the job task is performed. For instance, a refinery is in the process of expanding and constructing a new facility to meet current future petroleum production demands and there exists one particularly physically demanding task that is essential to the operation of the facility. The current facility has the same task and it has been determined that it is the cause of considerable physical distress to the workers. The most appropriate method of dealing with this situation would be to design the future task within the limitations of the worker to significantly decrease the risk of an incident. This provides a unique opportunity for the implementation of ergonomic and human factors design principles. Unfortunately, these opportunities for primary prevention are not as common as those of tertiary prevention.

The design principles may also be applied as tertiary prevention in efforts to accommodate and reduce the likelihood of exacerbating or facilitating recurring injury or illness. In this case, the job task or equipment may be altered to facilitate the task and re-engineer it such that it falls within the limitations of the worker. Such a process is dependant upon suitable information concerning the job task or equipment and its

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relationship to the injury or illness. For example, in the preceding incident, alterations in the design could be made relatively easily to the job task since it was in design phase of construction and not already in use, changes in designs are much cheaper than changes in product or equipment after manufacturing. In the case of tertiary prevention, mechanical aides could be introduced to lessen the physical or physiological load on the worker, however these solutions are not as desirable as primary prevention. Nevertheless, they should make a measurable and beneficial difference in the job task. Such preventive efforts are closely linked to secondary preventive efforts, an opportunity suited to primary care physicians specializing in occupational medicine. As noted by Viikari-Juntura & Riihimaki (1999) and Hensrud (2000a, b & c) these individuals have a particularly valuable role to play in secondary prevention efforts through early identification of the problem, such a proactive role can only benefit tertiary preventive efforts wherever primary preventive efforts are not feasible.

There are numerous examples of successful prevention efforts through design in the literature (Lincoln *et al.*, 2000; Bernacki *et al.*, 1999; Brisson *et al.*, 1999; NIOSH, 1997; NRC, 1999 & 1998). Unfortunately, there are few universal design interventions aimed at prevention due to the fact that all job tasks are different (NRC, 1998), however those that are similar in nature may benefit from cross-job task transfer of design principles. Whenever possible, past preventive solutions to similar job tasks should be sought out and improved upon (if possible) for use in the design of future job tasks. If no similar situations are found, the comprehensive ergonomic examination may be necessary. These design factors should then be implemented in conjunction with multicomponent programs with facets of psychosocial and organizational work components in order to enhance the likelihood of success as a means of work-related musculoskeletal disorder abatement.

1.2 Outline of Thesis

The research reported in this thesis is structured in such a way that it follows a logical progression. The issue of the control and prevention of occupational injury and illness was addressed in a series of steps beginning with the selection of an industry

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sector that has received little attention in this area. The industry selected for a focal point was also to be of vital interest to the economy of Alberta, as well as Canada. Thus the oil and gas industry was selected as the area of focus for research. The oil and gas extraction and processing industry employs approximately 450,000 Canadians (directly and indirectly), 215,000 of which are Albertans. Six percent of Canada's merchandise exports are comprised of oil and gas products. Roughly one-quarter of industry revenue is payment to government (federal and provincial), approximately $6 billion per year, $8 billion in 1997. Twenty-two percent of Alberta's government revenue, one half of the tax revenue, is derived from the oil and gas industry. The Canadian Association of Petroleum Producers (CAPP) states that in 1997, the industry directly contributed $8 billion to the Governments through provincial royalties, income taxes and land sale bonus payments. An additional $5.5 billion in crown and freehold royalty payments was also contributed. CAPP estimated oil, gas and gas by-products production value to be $34 billion in Canada for the calendar year 1997.

Although there has been a relatively large amount of research concerning the control and prevention of work-related musculoskeletal disorders in some industries, such as the manufacturing and service industries, there is a paucity of information in the scientific literature concerning the oil and gas worker from this perspective. The nature and control and possible prevention strategies for abating occupational musculoskeletal injuries and illnesses with respect to workers in the oil and gas industry, as well as the job tasks these workers are required to perform has not been studied in detail. A detailed review of literature revealed that the focus of all but a few scientific papers published in this area has been on the mortality rather than morbidity of the oil and gas worker (Satin *et al.*, 1996; Huebner *et al.*, 1997; Tsai *et al.*, 1997a; Tsai *et al.*, 1998). Those studies that were related to the issue of non-fatal injuries or illnesses are dated and were typically limited to offshore drilling platforms (Cooper *et al.*, 1987; Mueller *et al.*, 1987; Tsai *et al.*, 1991; Tsai *et al.*, 1997b). These workers are central to the economies of the province, the nation, as well as the global economy and hence worthy of examination.

With the selection of an industry to focus upon complete, the next step was the justification of the need for occupational injury and illness control and prevention to industry officials. Syncrude Canada Ltd., operators of the largest oil sands mining

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operation in the world and contributors to 15% of Canada's daily oil production agreed to participate in the endeavor. This justification is developed in Chapter 2 with the integration of ergonomics, a science not previously employed at this industrial organization, and loss management. The common focal point was the occupational injury and illness surveillance system. The organization had a very useful tool for surveilling incidents, but lacked a tool for addressing the root cause of incidents involving occupational injury and illness. Ergonomics is just such a tool and hence chapter 2 was written, and published for the first time for both audiences, as a comprehensive strategy for the integration of these two powerful tools in the efforts to control and prevent these incidents. Chapter 3 is related the issue of surveillance in that it addresses the need for a comprehensive and streamlined reporting system. Such a system is needed in order to ensure that accurate data concerning the relevant incidents is recorded and understood, and put to use to target and guide intervention, as well as act as a means of evaluating the success of these interventions. Chapters 2 and 3 are not limited to the issue of work-related musculoskeletal disorders and encompass all types of occupational injury and illness.

After justifying and integrating ergonomics within the established industry culture and loss management practice, the system was used to identify the most hazardous occupational tasks that workers were required to perform at the organization. From this list, one task was selected as the focus of further study. This task was industrial handwheel actuation and operation, which is vital to the oil and gas process industry, as well as many other sectors of industry. This task requires the generation of very large static tangential forces as well as large amounts of repetitious movements, and has been the direct cause of or at least a contributing factor to a very large number of occupational injuries and illnesses at the organization. Chapter 4 summarizes the current state of scientific knowledge concerning this task and addresses questions that should be addressed through ergonomic research.

Chapter 5 reports on a field study of the task of industrial handwheel operation which served as a preliminary assessment of the hazards of this task. The measurement techniques of electromyography (EMG), strength assessment and force exertions as well as psychophysics during handwheel operation were used to characterize this task. This

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was the first time such a study has been reported upon in the scientific literature. The results and observations were incorporated into a series of more robust laboratory-based experiments. These experiments were designed to address the task from the three most common approaches used in the area of control and prevention of work-related musculoskeletal disorders (Waters *et al.*, 1993).

Chapters 6 though 9 report research studies that were carried out in a laboratory setting. Chapter 6 addresses the issue of upper extremity adduction strength in various positions and trunk postures. Such motions are important to the task of handwheel actuation. Again, EMG and force exertion were measured. Chapter 7 addresses the maximum net tangential force generation capability and EMG activity exhibited by male experimental participants. This was the first time EMG was used to assess muscular characteristics in an experimental study of handwheel actuation. Chapter 8 addresses the issue of industrial handwheel actuation from a purely biomechanical perspective and focused upon the low back. A biomechanical model was used to calculate the forces acting upon the vertebral joints and to determine the likelihood of injury. In addition, the percentage of population capable of generating such forces was calculated. This was the first time such a model has been used to assess this task. Chapter 9 involves both psychophysical and physiological descriptions of the handwheel actuation task. The level of perceived exertion (psychophysics) as well as heart rate and oxygen consumption were measured under experimental conditions.

The results of chapters 4 through 9 were incorporated into a report submitted to Syncrude Canada Ltd. as justification for a series of design guidelines for industrial handwheels. These guidelines are to be used in the construction of new process facilities as part of a planned expansion and constitute an example of a form of primary occupational injury and illness prevention in industry. Such novel designs were put forth to control and prevent occupational injuries and illnesses in those workers charged with actuating and operating industrial handwheels.

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Chapter 2

Ergonomics, Loss Management, and Occupational Injury and Illness Surveillance in a Mid-Sized Industrial Organization[1]

[1] This chapter has been published in its present format. It is in the form of a two-part article. AMELL, T.K., KUMAR, S. & ROSSER, B.W.J. (2001). Ergonomics, Loss Management, and Occupational Injury and Illness Surveillance in a Mid-Sized Industrial Organization. Part 1: Elements of Loss Management and Surveillance. A Review. *International Journal of Industrial Ergonomics* 28(2), 69-84. AMELL, T.K., KUMAR, S. & ROSSER, B.W.J. (2001). Ergonomics, Loss Management, and Occupational Injury and Illness Surveillance in a Mid-Sized Industrial Organization. Part 2: Injury and Illness Profile. Sample Data. A Review. *International Journal of Industrial Ergonomics*. In press.

2.1 Part 1: Elements of Loss Management and Surveillance

2.1.1 Introduction

In some proactive mid- to large-sized industrial organizations comprehensive ergonomic programs and initiatives, as well as industrial occupational health and safety programs fall within the jurisdiction of an entity concerned with corporation-wide management of losses. This entity is comprised of members of the Corporate Loss Management Team. In essence, loss management team members employ principles that are designed to promote "the reduction of risk to people, the environment, assets and production" (Wilson, 1998). Effective loss management is carried out through the use of audits, inspections as well as complete integration of its principles with the organization's business model and corporate culture. Loss management may be thought of as a holistic set of elements designed to procure the safest and most efficient business model for the entire organization. Thus, ergonomic programs and initiatives may be thought of as an idealized means by which loss management carries out its mandate. Both systems are dependent upon one another for their success. Loss management utilizes ergonomic principles in the design of job tasks and systems while ergonomic programs utilize management for guidance, support and implementation.

Ergonomics is typically defined as a "multidisciplinary activity striving to assemble information on people's capacities and capabilities for use in designing jobs,

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products, workplaces and equipment" (Eastman Kodak, 1983). Ergonomic principles are habitually employed at two distinct levels, the so-called micro-ergonomic level whereby individual job tasks are considered, analyzed and optimized in terms of worker safety and productivity and the macro-ergonomic level whereby ergonomic principles are incorporated into management strategy and the overall business plan of the organization (Drury *et al.*, 1999; Imada *et al.*, 1986; Hendrick & Brown, 1984).

Under preferred circumstances, the principles of ergonomics are employed in the design phase of these tasks and tools and carried forward into the corporate culture. However, in practice, ergonomic principles are sometimes employed to address issues arising on an ad-hoc or post-hoc basis for existing jobs, products, workplaces or equipment. In these circumstances where ergonomics has not been incorporated into the business practice of the organization from the outset, management must become aware that issues under their control may benefit from ergonomic intervention. For example, in a micro-ergonomic situation, if a number of workers have been informing their supervisors, or the on-site medical or first aid clinics of injuries or illnesses sustained under occupational conditions, then those responsible for these incidents must be cognizant that 1) there is a problem that requires action and 2) that an ergonomic risk assessment or task analysis of the job or system might be necessary. A task analysis would then be carried out using whichever means appropriate, such as psychophysical, psychosocial, biomechanical, physiological and electromyographical variable analyses. These tests would then be used as a basis for the implementation and evaluation of an ergonomic intervention.

Concomitant with the optimization of worker productivity, worker safety is of the utmost importance from moral, legal and economic viewpoints. Ergonomically based design interventions targeted at controlling the occurrence of occupational injuries and illnesses are essential components of any loss management program. Accurate and timely information pertaining to occupational injuries and illnesses (surveillance) is important in order to precisely target workers, work groups and specific job tasks or systems for ergonomic intervention. These ergonomic interventions contribute significantly to the promotion, and maintenance of a safe, healthy and efficient work environment.

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Occupational injury and illness surveillance is thus an essential component of a comprehensive ergonomic program. It serves to notify the relevant individuals that a problem exists, and also acts as an objective means of evaluating the ergonomic program in terms of the occurrence of occupational injury and illness in the target population of employees. The goal of these programs is a desired reduction in the frequency and severity of incidents resulting in occupational injury and illness. Even though the success of the ergonomics program is directly linked to the issue of occupational injury and illness surveillance, unfortunately, this issue has received little attention in the ergonomic literature. To further compound the issue, those occupational surveillance systems that are in use may fail to provide management with a comprehensive and useful tool due to their shortcomings (Sorock *et al.*, 1997).

The purpose of this paper is to introduce the concept of loss management within the context of ergonomics. The role that ergonomics plays within the mandate of loss management is reviewed. Part 1 of this paper also introduces occupational injury and illness surveillance programs as an integral component of a comprehensive ergonomics program and inherently, a tool of loss management. For practical purposes, examples are drawn from an actual mid-sized industrial corporate loss management program.

2.1.2 The Industrial Organization

The mid-sized industrial organization drawn upon for example in this paper employs approximately 3600 full time workers and a varying number of contractors for an average total equivalent workforce of approximately 7,000 over the period from 1995 through 1999. The organization operates 24 hours per day, 7 days a week on a shift basis. The mandate of the organization is to produce a high-quality blend of synthetic oils that can be further upgraded and processed by other facilities into various petroleum products such as gasoline, jet fuel, plastics etc. Workers perform a variety of tasks, including tasks specific to open-pit surface mining, heavy machinery operation and maintenance, refinery process control and maintenance as well as administration.

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2.1.3 The Loss Management Program

The term loss management may be novel to some in the ergonomics field, however its principal components should not be foreign. A loss management program integrates the concepts of safety as well as identification, assessment and control of both hazards and risks for the express purpose of reducing harmful risks to people, environment, assets and production (Wilson, 1998). Hazards are typically defined as agents that could harm people, environment, assets or production. Agents include equipment, processes, activities and physical factors. Risk is a function of the probability of an unwanted incident and the potential severity of its consequences (Wilson, 1998). Normally ergonomics is concerned with the risks to people, i.e., prevention of musculoskeletal disorders, slips, trips and falls etc. However, since the majority of incidents involve some form of human error (Hoyos & Zimolong, 1988), be it physical or cognitive in nature, ergonomic principles are equally applicable to concerns involving the environment, processes and production. Loss management encompasses occupational health and safety management systems in this respect (Schweigert *et al.*, 1999).

Eleven elements of a loss management program are discussed by Wilson (1998), these are listed and described in table 2.1. Together, these elements serve as a platform for designing, constructing and operating the organization's facilities as well as controlling performance of the departments and individual employees within the organization. In order to be successful, these elements should be adaptive in nature, as well as have well-defined specific standards and objectives. The loss management program is participatory, with input from all levels of employees and should be copasetic with the type, size, and objectives of the business as well as the style of the organization (Wilson, 1998).

It is well established that managerial support, in addition to employee input is an important factor contributing to the success of ergonomic programs (Lincoln *et al.*, 2000; Bernacki *et al.*, 1999; Brisson *et al.*, 1999; Drury *et al.*, 1999; Melhorn *et al.*, 1999; Volinn, 1999; Moore, 1997; Taylor, 1990). It should be no surprise that first and foremost of the elements listed in table 2.1 is managerial support for loss management principles. According to Wilson (1998), managers must be aware that people are their most

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important asset and that loss management provides a significant opportunity for managing costs and improving operational reliability. Thus, the provision of safe job-tasks and systems as well as an optimized working environment (ergonomics) is key to successful loss management.

The second element in table 2.1 involves risk assessment, analysis and management. This element forms the basis of a large number of ergonomic studies published in the scientific literature (NIOSH, 1997). The control of ergonomic hazards is principal to any ergonomic program, whether micro- or macro- in nature. For example, according to Keyserling (2000a & 2000b) numerous workplace risk factors are associated with low back pain as well as upper extremity musculoskeletal disorders. These risk factors are comprised of both physical and psychosocial components such as extreme posture, excessive muscular force and physical fatigue, repetitive tasks as well as job satisfaction, worker perception of strain, discomfort and mental fatigue (Keyserling 2000a & 2000b; Ayoub, 1990a, 1990b & 1990c).

The third element listed in table 2.1 presents a suitable opportunity for the implementation of ergonomic principles in the design phase of a project. Tasks and equipment required for the future operation of the organization should be designed within the physical (muscular strength, anthropometrics, psychophysical) and cognitive (vigilance, displays and controls) limitations of the worker ultimately responsible for the utility of the task and equipment. The fourth element, operation and maintenance is directly linked to the third element in terms of ergonomics. Elements five, six and seven all have macro-ergonomic and human factors components in terms of efficient procedures and information flow.

Element eight involves reporting, investigating and analyzing incidents for the purpose of implementing follow-up actions aimed at reducing the likelihood that an incident will occur in the future. The surveillance of these incidents forms the basis for the justification and evaluation of the follow-up actions (e.g. ergonomic interventions and programs). The term 'incident' is used in these circumstances rather than 'accident' due to the fact that 'accidents' denote a lack of control and are typically a random occurrence. Since 'incidents' are manageable, preventable, and convey a notion of control, this is the preferred term.

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The surveillance system itself may be referred to as the loss control reporting system. This system usually takes the form of a central database. For optimum efficiency, the system should be linked to other databases within the organization such as human resources, the on-site medical or first aid clinics, and the industrial medicine department (Sorock *et al.*, 1997). Examples of the possible categories and variables monitored by the reporting system with particular reference to occupational injuries and illnesses are listed in table 2.2. Of importance is the inclusion of information concerning both actual and potential losses, item 4 in table 2.2. The recording of potential loss provides valuable insight into the so-called 'near miss' incidents where no actual incident or injury occurred, however the potential for an actual incident existed. This proactive component of the system provides a unique opportunity to prevent an incident before a loss is incurred.

The data input into the surveillance system are derived from specific incident investigations. Wilson (1998) describes the common injury and illness types, immediate and root causes of incidents as well as the incident investigation process. Table 2.3 is reproduced from Wilson (1998) and lists injury and illness cause in terms of energy flow. Accurate and timely knowledge concerning the immediate and root cause of an incident aids a great deal in its management and control. Table 2.4, also reproduced from Wilson (1998), lists common immediate and root causes of incidents. Immediate causes are typically easy to identify and usually involve substandard practices or conditions. Root causes form the basis of the immediate causes of the incident. They are typically more difficult to identify and may not be evident until after an incident has been thoroughly researched and investigated (Wilson, 1998). There is seldom one cause of an incident, and the majority of incidents are the result of a combination of causes. Each incident must be investigated thoroughly and actions taken to reduce the risk of recurrence. According to Wilson (1998) managerial solicitation of worker feedback and input into solutions and risk management is one of the most effective strategies of controlling root causes.

Proper investigation of the incident is important for accurate reporting. Investigation should 1) identify the substandard practices and procedures that caused the incident; and 2) identify the management system that failed to prevent the incident from

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occurring. Simply cataloging a list of facts and conclusions pertaining to the incident is not the end goal of the surveillance system. Thus, the most critical purpose of incident investigation is to 3) recommend remedial action and specific methods and strategies designed to prevent the incident from recurring (Wilson, 1998). Ergonomic principles may be ideally suited for remedial actions in the majority of instances. The overall structure of a systematic incident investigation model is listed in table 2.5.

Of particular interest to ergonomists are the loss control reporting system surveillance data pertaining to occupational injuries and illnesses. Unfortunately, as noted earlier, this aspect of the ergonomics program has not been addressed to any significant degree in the ergonomic literature. This aspect will be further discussed in section 2.1.6 of this paper.

Elements nine and ten listed in table 2.1 involve the need for accurate and timely information concerning hazards, facilities and the workforce as well as the relationship with the surrounding community respectively. Element eleven is related to program evaluation and is inextricably linked to element eight.

2.1.4 Ergonomics as an integral component of a Loss Management Program

The need for the assimilation of ergonomic/human factors principles with safety, and inherently loss management has only relatively recently become apparent to industry. This despite the acknowledged need for safety practices that have been apparent since the beginning of the industrial age (Hoyos & Zimolong, 1988), even though worker safety was not considered a priority until much later. Some industries have widely adopted ergonomics and integrated its principles within their organization to varying success rates, while others are only beginning this process (Volinn, 1999; Mital & Ghahramani, 1994). Yoder *et al.* (1973) recognized the benefits of integrating and employing human factors principles in conjunction with the safety program at Eli Lilly and Company in the United States. These authors stressed the need for enhanced design principles to prevent error-provocative features of systems, work physiology studies for compatible work load specifications and job design as well as electromyographical studies for use in optimal tool design and evaluation of work methods (Yoder *et al.*, 1973).

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As discussed in section 2.1.3, ergonomic principles may be applied in one manner or another, and to varying degrees to all of the loss management elements listed in table 2.1. Ergonomic principles provide a viable means through which loss management may introduce remedial action, based upon its reporting, investigating and auditing procedures. However, in order to be successful, accurate and timely information concerning the nature of the job task or system and the hazards and risks the ergonomic initiatives are designed to address is required. Thus, the success of the ergonomics program is directly linked to the accuracy and reliability of the loss control reporting system. This holds true for organizations where no similar loss management program exists as well, since all organizations must have at least some form of recording occupational injuries and illnesses.

In job tasks or systems where ergonomic principles were not employed from the outset, or perhaps improperly employed, risk factors may exist. These risk factors may eventually become apparent as precursors to the incident only after the occurrence of an occupational injury or illness. These risk factors are typically referred to as ergonomic risk factors where design concerns exist, or are referred to as health risk factors. Unfortunately, due to a variety of explanations, there has been a lack of stringent case-control studies prohibiting a direct linkage between some risk factors and the resulting injury or illness (Beahler *et al.*, 2000; Rivara & Thompson, 2000; Courtney *et al.*, 1997; Sorock *et al.*, 1997). Nevertheless, a sound reporting system will significantly improve the need for and evaluation of occupational injury and illness control efforts.

Ergonomic risk factors for specific incidents, injuries and illnesses must be properly identified and understood in order to control them (Keyserling, 2000a & 2000b; Burton *et al.*, 1999; Jarrard *et al.*, 1997). The loss control reporting system, when properly implemented, aids significantly in identifying the hazards and risks associated with a problematic job task or system. In addition to identifying the risks that may ultimately lead to an occupational injury or illness, accurate and comprehensive reporting also aids in understanding and eliminating risk of injury through intervention when acting as a means of program or initiative evaluation. Thus occupational injury and illness surveillance also plays a significant role in establishing the need for and evaluation of an

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ergonomics program or initiative. Section 2.1.6 discusses further the need for and basic elements of occupational injury and illness surveillance.

2.1.5 An Example of a Loss Control Reporting System

The loss control reporting system employed by the mid-sized industrial organization collects and maintains long-term data in computer database form in a manner identical to that listed in table 2.2. Table 2.2 is incomplete with respect to information not directly related to occupational injuries and illnesses and does not provide the full extent of information concerning elements 3.3 through 3.7. These types of incidents are beyond the scope of parts 1 and 2 of this paper as the focus of this discourse relates specifically to loss management as it is related to ergonomics and occupational injury and illness surveillance. Nevertheless, these other types are important in the full context of loss management.

The principles of loss management are well entrenched in the business plan and corporate culture of the organization. Each division of the corporation has a loss control assistant, a loss management coordinator and loss management advisors who work with safety personnel and managers. These loss management representatives are in turn directed by the corporate loss management team responsible for the organization as a whole. Together, this team manages the loss control data, carries out the incident investigations and identifies, implements and evaluates intervention efforts. The loss control reporting system itself is linked with the on-site medical centre as well as the human resources department in order to provide a holistic view of losses company-wide, particularly losses involving occupational injuries and illnesses.

2.1.6 Occupational Injury and Illness Surveillance

Ergonomic programs and initiatives aimed at controlling incidents involving occupational injuries and illnesses rely heavily upon accurate information pertaining to 1) which workers are incurring injuries/illnesses; 2) the job task or system believed to contribute to the injuries/illnesses as well as 3) the nature and incident character of the

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injury/illness. A multitude of other types of information concerning personal and job task related factors are also required. The systematic collection of these types of data is referred to as occupational injury and illness surveillance.

In order to be effective, surveillance of occupational injury and illness must be directly linked to preventative action (Baker & Matte 1992). Without this link, the entire process is questionable, as noted in section 2.1.1. According to Baker and Matte (1992), two levels of occupational injury and illness prevention are typically implemented in occupational health. The first level is primary prevention, which is the control of workplace hazards (i.e., ergonomics and loss management). Secondary prevention is related to the surveillance system. Secondary prevention must support the justification for and evaluation of primary prevention efforts (Baker & Matte 1992). According to Baker and Matte (1992) sound surveillance does not necessarily ensure the making of the right decisions, but it reduces the probability of making the wrong ones.

The surveillance system should satisfy two requirements; 1) it should properly identify cases of occupational injury or illness and 2) it should monitor trends of occupational illness or injury. Proper case identification is required to target an intervention of direct value to the affected individual and to others at risk of incurring the same injury or developing the same disorder (Baker & Matte 1992). Trends of occupational injuries and illness may be used to assess variations in 1) different industrial groups; 2) different geographic areas and 3) different time periods. For this to occur, a sound job classification system must be used and geographical and/or functional location grouping information must be known.

Numerous different strategies to surveil occupational injuries and illness have been reported in the literature. The use of workers' compensation data (Rosenman *et al.*, 2000; Biddle *et al.*, 1999; Bull *et al.*, 1999; Maizlish *et al.*, 1999; Pranksy *et al.*, 1999; Korrick *et al.*, 1994; Rossignol, 1994; Park *et al.*, 1992), trauma registries (Forst et al. 1999), hospital emergency room data (Hunting *et al.*, 1999; McCaig *et al.*, 1998; Hunting *et al.*, 1994), hospital discharge data (Sorock *et al.*, 1993) as well as union records (Lipscomb *et al.*, 1997) have all been utilized in one form or another for occupational injury and illness surveillance. Some authors have also compared multiple surveillance sources (Murphy *et al.*, 1996; Fingar *et al.*, 1992). Some have reported surveillance data

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from a network of internal, private occupational medicine clinics (Oleske *et al.*, 1992a & 1992b) while others have reported surveillance data from external, national programs in the United States involving the Occupational Safety and Health Administration (OSHA) 200 logs, the National Institute for Occupational Safety and Health (NIOSH) and the Bureau of Labor Statistics (McCurdy *et al.*, 1992, Hilaski, 1985).

Each of the above noted methods have positive and negative attributes (Pransky *et al.*, 1999; Courtney *et al.*, 1997; Sorock *et al.*, 1997; Wigglesworth, 1990). The external sources of surveillance, primarily workers' compensation insurance organizations, hospitals and OSHA in the United States only record occupational injuries and illnesses of the most severe nature, typically those that are reportable or compensable. This practice excludes the majority of occupational injuries at the organizational or plant level. Although useful for regional, national and inter- and intra-industrial comparisons from a public health point of view, these data are not as useful to specific industrial organizations at the company level as internal, customized occupational injury and illness surveillance systems. Furthermore, each system utilizes different definitions and coding strategies, thus inter-system comparisons usually require data modification and/or reduction techniques (Courtney *et al.*, 1997; Hilaski, 1985) in order to be useful. Although occupational injuries are usually defined in a straightforward manner due to their acute nature and definitive onset, occupational illnesses may not have such a definitive onset, such as in the case of work-related musculoskeletal disorders of the upper extremity or chronic low back pain and as a result may be improperly classified.

In addition to these shortcomings, there is evidence that workers' compensation insurance data under-report the true nature of work-related disorders or illnesses, particularly in cases involving the musculoskeletal system and repetitive trauma (Rosenman *et al.*, 2000; Biddle *et al.*, 1998). Biddle *et al.*, (1998) report that between 9% and 45% of workers file for benefits and that women and employees from smaller firms are more likely than others to file. The authors also report that acute conditions related to the current job were no more likely to lead to claims than chronic conditions. Rosenman *et al.* (2000) report contributing factors for their finding that only 25% of workers filed for compensation benefits. The strongest factors were associated with the severity of the

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condition, while other factors included increasing length of employment, lower annual income, and worker dissatisfaction with coworkers.

In addition to the underreporting of occupational injuries and illnesses based upon workers' compensation claims, there is also evidence of underreporting of the incident itself within the organization. Pransky *et al.* (1999) report that safety incentive programs negatively influence the nature of occupational injury and illness reporting. The authors support this statement with data from a survey that found that less than 5% of workers at a industrial facility officially reported an occupational injury or illness, however 85% had experienced work-related symptoms in the past year, 50% had persistent work-related symptoms and 30% reported either lost time or work restrictions. The authors report that the reason the workers did not report the incidents included fear of reprisal, belief that pain was an ordinary consequence of work activity or aging, lack of management responsiveness after prior reports and a desire not to lose use their usual job (Pransky *et al.*, 1999).

As noted above, currently employed occupational injury and illness surveillance systems at the organizational or company level may not provide management with the complete set of tools necessary to carry out a meaningful justification and evaluation of an ergonomic or loss management program (Sorock *et al.*, 1997). This is exemplified by the finding that there has been limited success in occupational injury and illness prevention (Courtney *et al.*, 1997; Sorock *et al.* 1997). The correct intervention is contingent upon proper identification of the problem. According to Courtney *et al.* (1997), epidemiological and etiological research on occupational injuries and illnesses is lacking hence it remains unclear whether the improper interventions are being employed, or whether the interventions are being inadequately employed (Courtney *et al.*, 1997). Perhaps the correct interventions (i.e. ergonomics) are being employed, however an ill-designed or ill-managed surveillance system has not detected an improvement and hence contributed to the shortcomings. It is the belief of the authors that based upon the review of literature and industrial experience, the answer is most likely a combination of the three. Thus, an improvement in the methods or strategies of either of these elements will ultimately improve the system as a whole and hence is worthy of our attention.

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Even with the aforementioned shortcomings, the occupational injury and illness surveillance system is still an important component of the loss management program and in turn, the ergonomic strategy at the organizational or company level. Unfortunately, only two relevant articles were found in the literature that describe the nature, and implementation of an organizational level system. Sorock *et al.*, (1997) provided three perspectives on occupational injury and illness surveillance systems, drawn upon examples from the Ford Motor Company while Mitchell *et al.* (1993) describe the application of such a system at an integrated manufacturing facility.

Sorock *et al.* (1997) reviewed three emerging surveillance system approaches for the enhancement of occupational injury and illness surveillance. All three perspectives presented by Sorock *et al.*, (1997) are found applied in the integrated loss management program loss control reporting system employed by the mid-sized industrial organization. The three perspectives were; 1) narrative data analysis, 2) data set linkage, and 3) the need for comprehensive company-wide surveillance systems. The authors state that improved description of work exposures and related injuries, which ultimately leads to improved injury etiology, is limited in its capacity due to incomplete and poor quality data collected at the time of reporting (Sorock *et al.*, 1997).

Sorock *et al.* (1998) recommend that 1) narrative text in addition to coded data be included in the incident report in order to supplement the databases' qualities; 2) data sets within the organization concerning occupational injuries and illnesses and work-history data (human resources data) should be linked with one another and 3) that company-wide surveillance systems be developed in order to expedite the use of epidemiologic data for occupational injury and illness prevention activities. The authors note that with the technological advances in data capture, analysis and presentation (e.g., large computer-based corporate databases), this task is less daunting than once previously thought.

The recommendations put forth by Sorock *et al.* (1997) support and concur with the loss control reporting system component of a loss management program as discussed in section 2.1.2. This underscores the association between loss management principles and the ergonomic programs they employ and the need for comprehensive occupational injury and illness surveillance. Narrative texts, which are the result of the incident investigations, are typically included within the reporting system. According to Sorock *et*

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al. (1997), narrative texts supplement coded data by providing details concerning each specific incident. These texts may be analyzed and recoded at a later data as well should the need arise. The narrative texts also permit manual or computer based key-word searches to identify specific injury hazards that may not be identifiable through the coded data (Sorock *et al.*, 1997). Unfortunately, the use of narratives results in inconsistent texts and differences in the clarity, level of detail and wording may ensue.

The linkage of data sets allows the integrated system to take advantage of elements of more than one data set linked by a common element (Sorock *et al.*, 1997). The combined data sets allow for a more comprehensive integrated data set than any one set can offer, since common elements are shared, while each system adds or removes information based upon their needs. Regrettably, certain restrictions may have to be introduced because such all-encompassing data sets have the potential for mismanagement.

The comprehensive company-wide surveillance system proposed by Sorock *et al.* (1997) is quite similar in principle to the loss control reporting system, although the latter is larger in scope. The direct connection between the occupational injury and illness surveillance system and the initiatives and control efforts aimed at reducing their occurrence and severity in an organization-wide format is a powerful tool when implemented correctly. This type of system promotes a proactive atmosphere rather than the simple reactive atmosphere associated with a stand-alone occupational medicine clinic injury and illness summary report. Sorock *et al.* (1997) highlight the timeliness and accuracy of such an organization-wide system in addition to its ability to place intuitive data concerning occupational injuries and illnesses in terms of rates per hours worked and costs into the hands of managers. One limitation of this method is that implicit coding structures are required in order to facilitate comparisons within an organizations numerous divisions and plants.

The loss management loss control reporting system currently being used by our industrial partner already contains a narrative explaining the incident details, as well a great deal of other information concerning the incident from both an occupational medicine perspective as well as a loss management perspective. It is also linked in a limited capacity to work history data and has been company-wide since its inception. We

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suggest that in addition to linkage with the work-history data which provide exposure times in terms of hours worked, schedules etc., limited rudimentary data also be included from the on-site medical or first-aid clinic. These data could be managed in such a manner to protect worker confidentiality related to medical history and diagnosis through the encoding of the worker's name and employee number, and any other immediately identifiable data in a separate database and only providing access to the pertinent information such as the body part injured, that nature of the injury, age, height, smoking history etc. to loss management. The system would also provide the medical staff with limited access to loss management information.

Sorock *et al.* (1997) propose 6 general design criteria for an occupational injury and illness surveillance system based upon their perspectives of the issue. They propose that 1) information collected must go beyond only reportable incidents, i.e., those claims required by law to be reported (worker's compensation, OSHA 200 forms in the United States); 2) supervisors be informed of any incidents to employees assigned to them and also should be included in the associated incident investigation; 3) minimal data sets recorded include a narrative with information concerning how the incident occurred and the tools or equipment involved; 4) that systems be designed to be capable of computing incident rates according to organizational units within the plants, divisions etc., as well as by job classification, age group, gender etc.; 5) systems must incorporate costs associated with occupational injuries and illnesses and, 6) system records should be computerized for optimal efficiency. The loss control reporting system employed by our industrial partner meets and exceeds these criteria for occupational injury and illness surveillance.

Mitchell *et al.* (1993) listed the following three criteria as the basis for their injury surveillance system; 1) a coding system based upon the clinical injury at the time the injured individual is initially seen at the clinic; 2) a severity scale incorporated into the system and, 3) ease of automation. The system implemented was based upon the Abbreviated Injury Scale (AIS), which categorizes injuries by anatomic region, type of injury and injury severity (Mitchell *et al.*, 1993; Committee on Medical Aspects of Automotive Safety, 1990). The system required some modification for workplace implementation and was found to adequate, however, the severity index did not predict

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lost work time nor disability. The system was better suited to acute injuries than to illnesses.

The approaches to occupational injury and illness noted above suit the needs of the loss control reporting system in terms of both the justification and evaluation of ergonomic programs aimed at injury and illness control.

2.1.7 The Integration of Ergonomics, Loss Management and Occupational Injury and Illness Surveillance

Ergonomic design principles are an ideal avenue through which loss management can exercise its mandate to procure the safest and most efficient business model. This is attained through the reduction of risk to people and product, as well as to company assets and the environment. The integration of ergonomic principles within the corporate culture and business model is highly recommended due to the complimentary relationship between the two disciplines. Both are interdependent in terms of the need for remedial action to address a source of loss for the company and means by which this remedial action may be carried out. The occupational injury and illness surveillance system component of the loss management loss control reporting system forms a common bridge between the two entities, which will, under adequate implementation of the respective programs, improve the efficiency of ergonomic interventions. A sound reporting system serves as both the source of information concerning the need for ergonomic intervention, and a worthy method of evaluating the intervention in terms of it's success and the degree to which it has achieved its goals.

The second part of this paper describes the occupational injury and illness profile of a mid-sized industrial organization. These data were extracted from a loss control reporting system and serve to monitor the occupational health of the organization's workforce and alert those managers responsible of areas (types of jobs, teams, locations etc.) that are in need of immediate attention. These data serve to compliment the content of this paper in terms of the value that ergonomics provides to a loss management program.

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2.1.8. Conclusion

The role that ergonomic design principles contribute to a loss management program is based upon the complementary nature of the ideologies. Both systems may be integrated in a seamless program designed to provide the safest and most efficient working environment. Although the concept may be novel to some in the ergonomics field, the relationship is natural and is bridged by the common need for a comprehensive occupational injury and illness surveillance system. We believe that as loss management principles become more entrenched within industry, this will facilitate the even broader incorporation of ergonomics within industry as well. A thorough occupational injury and illness surveillance system will serve both programs by providing a comprehensive method of evaluating ergonomic interventions.

2.2 Part 2: Occupational Injury and Illness Incident Profile

2.2.1 Introduction

The relationship between ergonomic programs, the elements of loss management and occupational injury and illness surveillance was the focus of the first part of this two-part paper. Ergonomics was discussed in terms of a comprehensive loss management program as a means by which loss management may intervene in problematic areas. The reliance of ergonomic programs, initiatives and interventions on loss management elements, particularly its integrated approach to occupational injury and illness surveillance by means of a corporate-wide loss control reporting system was also discussed. This second part of the paper provides examples of the information that a comprehensive loss management loss control reporting system produces. Although the reporting system collects many types of data, the information concerning occupational injuries and illnesses is most pressing from an ergonomic viewpoint and hence is the focus of this paper. Occupational injury and illness surveillance provides an objective tool for establishing the need for ergonomic program intervention as well as a sound method of evaluating such an intervention. For example, properly employed surveillance

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may reveal that there are a disproportionate number of low back injuries in a particular operational division of a plant. Management would then be informed of this and order an ergonomic assessment, which reveals that a new manual material handling task has recently been added to the workload of employees in this division and that this task is unsafe in its present form. An ergonomic design intervention could then be implemented and evaluated using the pre- and post-intervention surveillance data to justify and evaluate the intervention. Although this scenario seems logical, simplistic and adherent to good experimental design, unfortunately there is a lack of information in the ergonomic literature regarding the issue and importance of occupational injury and illness surveillance systems as they relate to ergonomic programs, their justification and their evaluation.

It is well established that occupational injuries and illnesses account for a significant portion of lost workdays in industry (Riihimäki, 1995). When an employee is injured or becomes ill, the cost of that injury or illness is not easily calculated due to a variety of factors. Aside from direct medical, indemnity and risk management costs associated with an injury or illness, there are also ancillary or indirect costs such as lost productivity, overtime associated with compensating for injured workers, work-site modification and/or supervision of injured workers, recruitment and retraining of replacement workers, human resources department costs for managing injuries and unfortunately, under certain circumstances, legal fees (Riihimäki, 1995). Together, these factors combine to represent a significant opportunity for cost reduction since occupational injuries and illnesses are manageable and in many instances, preventable.

Compensation for injuries and illnesses sustained by workers under occupational conditions culminates in a substantial financial burden to industry, as well as the Canadian healthcare system. Canada is not alone, however, as occupational injuries and illnesses impart a significant burden upon most industrialized nations, including the United States, particularly with respect to the burgeoning number of work-related musculoskeletal disorders (Keyserling, 2000a & 2000b). For example, the Canadian province of Alberta's expenditures on workers' compensation claim costs increased to $470 million in 1997, $62 million over-budget and representing a 3% growth over 1996 costs (Alberta Labour, 1998). In 1998, this figure increased substantially to $555 million,

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$90 million over-budget and representing a 15% growth over 1997 costs (Alberta Labour, 1999a & 199b). In 1999, $821 million was spent on claims, 45% over budget and 75% over the total claim cost in 1997 (Alberta Labour, 2000). In light of these staggering costs, the need for occupational injury and illness control research and ensuing remedial action has never been more apparent.

Since expenditures continue to rise, current initiatives are not providing adequate solutions to the problem of occupational injuries and illnesses and are in need of revision. Interventions at the plant level are contingent upon proper identification of the problem. Unfortunately, it is unclear whether the improper interventions are being employed, or whether the interventions are being inadequately employed (Courtney *et al.*, 1997; Sorock *et al.*, 1997). Another issue that remains unclear is whether the proper interventions are being employed, and the efficacy of the intervention is being improperly assessed by a poorly designed, substandard occupational injury and illness surveillance system. Once comprehensive occupational injury and illness surveillance is employed, such as in the case of the mid-sized industrial organization example given in the first part of this paper, then ergonomic interventions may be designed, implemented and evaluated with greater precision.

Occupational injury and illness control and prevention represents an avenue of substantial revenue recovery if this problem can be attenuated. Ergonomics has been shown to be an effective method of addressing the problem of occupational injuries and illnesses by the General Accounting Office in the United States (1997), as well as researchers and focus groups at the National Institute for Occupational Safety and Health (1997) and the National Research Council (1998, 1999). Numerous other researchers have also reported on the benefits of ergonomics (Lincoln *et al.*, 2000; Bernacki *et al.*, 1999; Brisson *et al.*, 1999; Drury *et al.*, 1999; Melhorn *et al.*, 1999; Volinn, 1999) to varying degrees of success. Thus, in terms of a comprehensive loss management program, ergonomic initiatives based upon and evaluated by a proficient occupational injury and illness surveillance system will greatly enhance the efforts made by industry towards decreasing the frequency and the severity of these incidents.

The purpose of the second part of this paper is two-fold. The primary purpose is to present examples of the meaningful data that a loss management loss control reporting

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system provides. The secondary purpose is to provide an injury and illness profile of a mid-size industrial organization based upon loss management perspective data and show how these data could be used to guide and evaluate ergonomic initiatives.

2.2.2 The Loss Control Reporting System

The loss control reporting system employed by the mid-sized industrial organization collects and maintains long-term data in computer database form. Data concerning all aspects of a loss management program are recorded. These items include information pertinent to worker occupational injuries and illnesses, environmentally related incidents, incidents involving assets such as security, and damage as well production related incidents. For a detailed account of the variables monitored by the loss control reporting system, please refer to table 2.2 in part 1 of this paper. The information is typically input into the database within one day following an 'actual' or 'near miss' incident as well after a visit to the on-site medical centre or incident investigation.

Data are layered systematically within the database and may be browsed from numerous origins. For example, data may be sorted by time, by phase of operation, by visibility, by severity, frequency and recurrence etc. It is possible to focus on one particular type of incident, perhaps one involving motor vehicle collisions under winter driving conditions resulting in bruising or lacerations to the arms of vehicle occupants. Conversely, one may focus on the more general issue of musculoskeletal injuries of the sprain variety incurred by custodial staff. At the most precise level of the system, a narrative outlining the particulars of the event (sex, job title, location, etc.) and its investigation (basic and root causes, etc.) is found.

The basic cause of the incident, as well as the supplementary actions, conditions and factors associated with the incident in loss management terms is another possible method of sorting the data. The numerous variables describing each incident allow for an equal number of means by which to analyze the data. With such a large volume and depth of data, the data analysis approach must be question driven as the ability to customize and report on virtually any issue addressed by the loss control reporting system is at hand. For

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this reason only examples of what type of information may be extruded from the database are presented herein.

2.2.3 Method

Surveillance data pertaining to occupational injuries and illnesses serve as a means of justifying the need for an ergonomic intervention. These data also serve as a means of evaluating the ergonomic intervention in terms of it efficacy and impact on the frequency and severity of incidents. To show the usefulness of such information, loss management data pertaining to occupational injury and illness at the mid-sized industrial organization were extracted for the ten-year period beginning January 1, 1990 and ending December 31, 1999. Incident data were sorted by three distinct levels, each with two variables; the type of incident (occupational injury or illness), the organization responsible for the injured worker (the company or a contractor) as well as the severity of (actual or near miss). Thus, eight values were reported for each incident variable examined.

Three variables related to occupational injuries and illnesses were selected, these were; the incident character (overexertion, slip, trip, fall), the body part injured (head, back, hands) and the nature of injury (sprain, bruise, laceration). In addition to these variables, the five categories of incident cause related to each occupational injury and illness were also extracted. These variables were the basic cause (inadequate design, low work standard); substandard actions (unsafe position; unsafe lifting or carrying); substandard conditions (defective equipment, inadequate warning system); contributing factors (tried to avoid extra effort) as well as remedial actions referred to as work to control variables (improve design). Although any number of variables may be extracted and analyzed, we felt that these were most pertinent to those in the ergonomic field. Furthermore, these data were not limited to incidents involving the musculoskeletal system, particularly musculoskeletal disorders of the upper extremity and low back pain as is frequently the case in the ergonomic literature.

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2.2.4 Results

A total of 14,407 incident characters were recorded by the loss control reporting system during the ten-year period ending December 31, 1999. These incidents ranged in severity from minor cuts and lacerations (majority) to disabling injuries (minority). Table 2.6 lists the incident character distribution sorted by type of incident, organization and severity for this time frame. It should be noted that, as with the cause of incidents, each incident character, body part injured and nature of injury may have multiple factors and attributes and hence these totals do not equal with the number of 'true' injuries or illnesses based upon the individual worker. This also holds true for the cause data. Typically, the most frequently noted incident character for injuries were of the struck by or against variety, along with those incidents attributed to overexertion. The most frequently noted incident character for illnesses were either 'other' or exposure, indicating a need for more top-level categories since some data may not be encoded as efficiently and objectively as possible. In these instances, the narratives described by Sorock *et al.* (1997) would be of use. More injury incident characters involve contractors than company employees while the opposite is noted for illnesses. More near miss incident characters are reported for company employees than contractors.

Table 2.7 lists the injured body part distribution sorted by type of incident, organization and severity for this time frame. The most frequently injured body parts were the fingers, back, head and eyes while the body part most frequently affected by illness were also restricted to the head, back, trunk and upper extremities. The number of reported incidents involving contractor injuries was greater for injuries while less for illnesses, a trend noted in table 2.6 as well.

Table 2.8 lists the nature of injury distribution sorted by type of incident, organization and severity for the time frame studied. The majority of injury incidents were sprains, bruises and cuts, while the majority of illness incidents were exposures and sprains. More actual incidents than near miss incidents were recorded.

Tables 2.9 through 2.13 list the incident cause data sorted by type of incident, organization and severity for the 10 year period examined for the five types of causes respectively. Table 2.9 lists the basic cause distribution. Low work standards and

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inadequate design were frequently noted as the basic cause of injuries while physical problems, low work standard and 'other' causes were noted as the cause of illnesses. Table 2.10 lists the substandard actions contributing to the incident. Workers being inattentive to ambient job hazards and utilizing unsafe work positions were the most frequently noted types of injuries and illnesses while failure to warn or secure equipment contributed to over 20% of near miss occupational illness incidents. Table 2.11 lists the substandard conditions contributing to each incident. Congested areas and defective equipment are frequent causes of injuries while defective equipment, inadequate ventilation and inadequate warning systems are frequent causes of illnesses. Other substandard conditions are also noted as significant factors.

Table 2.12 lists the contributing factors to each incident. Trying to avoid extra effort is consistently cited as the major contributing factor to incidents. Table 2.13 lists the work to control (remedial actions) directives suggested concerning each incident. Personal factors such as proper instructions and informing department personnel were cited as the most frequent follow-up action for both injuries and illnesses. Design improvements were cited as remedial action in 5% and 7% of actual injury cases for company employees and contractors respectively, while 3% near misses in each organization respectively for injuries. Design improvements were suggested in 10% and 13% of company employees and contractors respectively for actual illnesses.

2.2.5 Discussion

Occupational injury and illness profiles based upon surveillance data at the plant and organization level have been published in the past (Mital & Ghahramani, 1994; Oleske *et al.*, 1992a & 1992b), and some have even included some causation data (Kingma, 1994), however the majority of profiles have been based upon workers' compensation insurance or similar large information systems (Rosenman *et al.*, 2000; Biddle *et al.*, 1999; Bull *et al.*, 1999; Fine, 1999; Maizlish *et al.*, 1999; Pranksy *et al.*, 1999; Korrick *et al.*, 1994; Park *et al.*, 1992). This type of information is useful for the purpose of establishing broad national or sector-based trends and are often cited at the beginning of scientific papers as one basis for ergonomic intervention, however more

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precise, focused data at the plant or organization level are required to establish the need for and to guide ergonomic programs and initiatives. Furthermore, workers' compensation data only include the most severe incidents and exclude the majority of incidents that are non-compensable in nature. The loss management loss control reporting system described in the first part of this paper and elaborated upon in terms of an occupational injury and illness profile in the second part of this paper is precisely what is required from both an ergonomic viewpoint and a loss management viewpoint.

Based upon these data, it could be determined that injuries and illness are dramatically different in terms of their profile, a finding clearly in support of those claims made by Driscoll (1993). Clear delineation between the definition of injury and illness must exist within the classification hierarchy of the system in order to take full advantage of it. Without such delineation, the appropriate intervention may not be employed. The need for a stable classification throughout the entire system, from job descriptions to nature of injury cannot be understated. This holds particularly true for the multi-dimensional and multifactorial nature of injuries (or illnesses?) to the musculoskeletal system, such as work-related musculoskeletal disorders of the upper extremity and low back pain. Furthermore, overuse of the 'other' category within some sub-levels of the surveillance system may lead to loss of useful information. The customized surveillance system should address this issue.

A detailed analysis of the occupational injury and illness profile of the industrial organization is beyond the scope of this review, however since our purpose is to introduce the reader to the benefits of comprehensive surveillance based upon a loss management model, a limited analysis will be provided. As noted above, incidents involving injury and illness exhibit different properties. Both the incident (incident character, body part injured and nature of injury) as well as the cause of the incident (basic cause, substandard actions and conditions, contributing factors and work to control actions) were significantly affected by whether the incident resulted in an injury or illness. This also held true for whether company employees or contractors were the population examined as well as whether actual or near miss incidents were recorded.

The frequency of injury reports is significantly greater than illness reports based upon tables 2.1 through 2.8. Near miss incidents are reported less frequently by

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contractors than by company employees, however these data show that at least they are being reported to some extent. For example, there was a ratio of 1.21:1 injury near misses reported by company employees to actual incidents in this population for the incident character. Unfortunately, the near miss incidents reported by contractors was less than 0.19:1 for this same variable. This despite the fact that contractors are typically injured more frequently than company employees, however company employees typically become ill more frequently than contractors. The discrepancy of reporting near miss incidents could be due to the observation that safety may play a larger role in the corporate culture of the company's workforce versus its contractors. The company employees may take pride in injury and illness avoidance based upon reporting near misses.

Although reporting near miss incidents is of obvious prevention and control value, the practice is limited. One limitation of reporting these types of incidents is the inability to accurately predict the potential injury or illness associated with a near miss within the surveillance system. This value must be used with caution as the potential severity of an incident resulting in an occupational injury or illness is difficult to ascertain. Mitchell *et al.* (1993) attempted to predict disability and lost time from actual incidents and found it to be of little value. Thus attempting to do so with near miss data provides nothing more than a crude approximation. Nevertheless, this type of data does show areas of potential hazard and risk and should be addressed accordingly through remedial action.

The incident cause data provided by the loss management loss control reporting system relevant to ergonomics include those variables with a design component. For example, inadequate design was frequently cited as the third most common basic cause of incidents recorded by the system over the past ten years. Unsafe positions as well unsafe lifting or carrying were frequently noted as substandard actions contributing to the occupational injury or illness. In addition to these factors, improved design, equipment and standards were also noted as modes of remedial action. These recommendations are directly suited for ergonomic interventions and are copasetic with the mandate of a company-wide ergonomics program.

The incident profile derived from a loss management based occupational injury and illness surveillance system can be put to great use by ergonomists. For example, the

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need for focused attention from management and supervisors regarding motivation, incentives and attitudes towards ergonomics and safety may be identified through the number of near misses reported by the system before these factors manifest in an actual incident. Under these circumstances, ergonomic interventions concerning the training of new employees and the encouragement of safe work practices to compliment physical ergonomic design interventions would be of significant value. This could be accomplished through ergonomic or safety theme weeks whereby certain high or low profile incidents are brought to the employee's attention through posters, emails and supervisor discussions. Problems associated with organizational processes and information processing which were identified through the text narratives and root causes of incidents could be streamlined to minimize barriers to effective communication and effective task completion based upon macro-ergonomic principles in addition to accepted change management practice. These are only a few of the many examples that describe the usefulness of a loss control reporting system and its parent comprehensive loss management program to ergonomists. Ergonomists should be encouraged to seek complete information concerning the corporate culture in order to fully benefit from the integration of loss management and ergonomics.

2.2.6 Conclusions and Recommendations

The purpose of part two of this paper was to present examples of the usefulness of the information provided by a comprehensive loss management loss control reporting system. Another purpose was to provide an injury profile of a mid-sized industrial organization based upon these data. These data are ideal for justifying, targeting and evaluating ergonomic initiatives at all levels of an organization. Furthermore, in due course, these data will improve the efficacy of ergonomic programs through a more stringent evaluative model. Ergonomics is an ideal means by which loss management principles may be exercised, as described by the limited data provided herein. There is the potential for more detailed information available to the ergonomists and occupational health personnel than is presented here. Those employing ergonomic principles against the frequency and severity of occupational injuries and illnesses should be cognizant that

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such all-encompassing strategies exist and may be an extremely useful tool in the effort to promote the safest and most efficient workplace possible.

Based upon the information presented in this two-part paper, we recommend that:

1. Those employing ergonomic programs familiarize themselves with the corporate culture of the organization and industry.
2. Full comprehension of the strategies used by and the goals of the ergonomics program are clearly delineated from the outset.
3. The degree to which loss management principles and occupational injury and illness surveillance are employed within the organization must be known and understood.
4. Wherever possible, the principles of loss management should be employed concomitant with ergonomic principles in order to procure the safest and most efficient work environment with minimal impact upon workers, the environment, assets and production of the organization.

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Table 2.1: The eleven elements of loss management (LM) based upon discussion put forth by Wilson (1998).

Loss Management Element	Description
1. Management leadership, commitment and accountability	Managers provide resources and play a key role in planning, organizing, leading and maintaining the program. Managers should integrate LM with company activities, business plan and business culture.
2. The assessment, analysis and management of risks	Managing risks is a continuous, dynamic process that involves the elimination of hazards. This is accomplished through monitoring, identifying, assessing, evaluating and controlling the risks.
3. Design, construction and start-up	The integration of LM principles should begin at the onset of the project. These include monitoring and stewardship activities as well as specific objectives for: design standards and practices, risk assessment, quality control and pre- and post-start-up reviews.
4. Operations and maintenance	This is dependent upon: effective procedures and practices, qualified staff, structured inspections, reliable safety systems, timely and accurate updating regarding change, and a thorough work-permit system.
5. The competency and training of employees	Managers must establish, adequately fund and employ carefully designed systems for the selection, placement, ongoing assessment and effective training of employees.
6. The competency and integration of contractors	Contractor activities must be compatible with organizational standards, policies, procedures, practices and business objectives.
7. Change management	Change is a necessary reaction to changing markets and regulatory laws and must be managed accordingly.
8. Reporting, investigating and analyzing incidents, and taking follow-up action	Precise recording of 'actual incidents' and 'near misses' is integral the management of losses. The information is used to base corrective action, preventative efforts and evaluation.
9. Collecting information and documentation on operations and facilities	In order to control losses, accurate and timely information concerning the workforce, operations, facilities, materials, hazards and regulatory requirements must be available.
10. Community awareness and emergency preparedness	Communities require assurance that nearby industries comply with safety and environmental standards such that public health and safety are maintained.
11. The evaluation and continuous improvement of programs	Continuous improvement of the LM program is a necessity. Operations or projects must be assessed at appropriate intervals to ensure that all elements of the LM program are meeting or surpassing their objectives.

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Table 2.2: Examples of the variables and categories monitored by the loss control reporting system.

1. Organization	1.1 Company		
	1.2 Contractor		
2. Condition	2.1 Visibility	2.1.1 Clear; Fog; Rain; Snow; Bright; Dim; Dark; Dusty	
	2.2 Road condition	2.2.1 Dry; Wet; Slippery; Soft	
	2.3 Phase of operation	2.3.1 Normal, Shutdown	
3. Type	3.1 Injury [a]	3.1.1 Incident Character	3.1.1.1 Struck By or Against; Caught on or Between; Exposure; Slip; Trip; Fall; Contact With; Overexertion; Foreign Body; Other
		3.1.2 Body Parts Injured	3.1.2.1 Eyes, Head (includes face, neck); Fingers (includes thumb); Hands (includes wrist); Arms (includes elbow); Back; Knees; Legs; Trunk (includes chest, hips, shoulders); Feet (includes toes, ankles); Internal; Other
		3.1.3 Nature Of Injury	3.1.3.1 Cut; Fracture; Allergy; Sprain; Scrape; Shock; Welding Flash; Bruise; Crush; Foreign Body; Burn; Exposure; Puncture; Dermatitis; Other
		3.1.4 Injury Severity	3.1.4.1 Disabling Injury; First Aid; Medical Aid
	3.2 Occupational Illness [a]		
	3.3 Security		
	3.4 Environment		
	3.5 Damage		
	3.6 Production		
	3.7 Fire		
4. Severity	4.1 Actual	4.1.1 Minor	
		4.1.2 Serious	
		4.1.3 Major	
	4.2 Potential [b]		
5. Frequency	5.1 Rare		
	5.2 Occasional		
	5.3 Frequent		
6. Recurrence	6.1 Low		
	6.2 Medium		
	6.3 High		
7. Cause	7.1 Basic Cause	7.1.1 Inadequate design or construction; Low maintenance standards; Low work standard; Lack of knowledge or skill; Improper motivation; Warn out from normal use; Low Purchasing Standards; Overlooked by inspection; Physical problems; Insufficient planning; Other	
	7.2 Substandard Actions	7.2.1 Operating without authority; Tampering or unauthorized removal; Unsafe position; Trying to gain or save time; Working unsafely on moving or dangerous equipment; Failure to warn or secure; Unsafe lifting or carrying; Inattentive to job hazards; Procedural deviation; Other	
	7.3 Substandard Conditions	7.3.1 Inadequately guarded; Inadequate ventilation; Congested area; Defective equipment [materials, tools]; Inadequate illumination; Substandard housekeeping; Inadequate Warning System; Other	
	7.4 Contributing Factors	7.4.1 Tried to avoid extra effort; Exposed to extreme temperature; Insufficient line-up/follow-up by Supervisor; Other	
	7.5 Work to Control	7.5.1 Training required; Instruct persons involved; Re-assign person(s) involved; Improve house keeping; Require procedure or revision; Inform department personnel; Improve compliance with standards; Repair, replace or provide equipment; Implement corrective action; Improve inspection; Improve design; Improve protective equipment; Improve rules and regulations; Other	

a Occupational Illnesses are classified in the same manner as Occupational Injuries.
b Potential incidents are classified in the same manner as actual incidents.

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Table 2.3: Injury and illness cause in terms of energy flow, derived from Bird and Germain (1992).

Type of Energy Delivered	Primary Injury Produced	Examples and Comments
1. Mechanical	Displacement, tearing, breaking and crushing, predominantly at tissue and organ levels of body organization.	Injuries resulting from the impact of moving objects such as falling objects and from the impact of the moving body with relatively stationary structures such as in falls and motor vehicle collisions. Overexertion injuries [muscular strains and sprains] and Cumulative Trauma Disorders fall within this category. The specific result depends upon the location and manner in which the resultant forces are exerted. The majority of injury is in this group.
2. Thermal	Inflammation, coagulation, charring and incineration at all levels of body organization.	First-, second- and third-degree burns. The specific result depends on the location and manner in which the energy is dissipated.
3. Electrical	Interference with neuromuscular function and coagulation, charring and incineration at all levels of body organization.	Electrocution, burns, interference with neural function as in electroshock therapy. The specific result depends on the location and manner in which the energy is dissipated.
4. Ionizing Radiation	Disruption of cellular and sub-cellular components and function.	Reactor incidents, therapeutic and diagnostic irradiation, misuse of isotopes, effects of fallout. The specific result depends on the location and manner in which the energy is dissipated.
5. Chemical	Generally specific for each substance or group.	Includes injuries due to animal and plant toxins, chemical burns, as from KOH, BR_2, F_2 and H_2SO_4 as well as the less gross and highly varied injuries produced by most elements and compounds when given in sufficient dose.

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Table 2.4: Common immediate and root causes of incidents as listed by Wilson (1998).

Immediate Causes	
Substandard Practices	Substandard Conditions
Operating equipment without authority	Inadequate or improper protective equipment
Failing to follow established procedures	Defective tools, equipment, materials
Making safety devices inoperable	Fire and explosion hazards (hidden)
Failing to use personal safety equipment	Poor housekeeping, disorder workplace
Servicing equipment that is in operation	Hazardous environmental conditions
Working while under the influence of alcohol/drugs	Inadequate training, expertise, etc.
Root Causes	
Personal Factors	Job Factors
Inadequate physical/physiological capability	Inadequate leadership/supervision
Inadequate mental/psychological capability	Inadequate engineering
Physical or physiological stress	Inadequate purchasing
Mental or psychological stress	Inadequate maintenance
Lack of knowledge	Inadequate tools and equipment
Lack of skill	Inadequate work standards

Table 2.5: Incident investigation model as listed by Wilson (1998).

Loss	**Incident**	**Immediate Cause**	**Root Cause**	**Lack of Control**
People	Contact with energy	Substandard practices	Personal factors	Inadequate program
Environment	Contact with substances	Substandard conditions	Job factors	Inadequate program standards
Assets		Substandard quality and design	Design factors	Inadequate compliance to standards
Production				

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Table 2.6: The distribution (%) of types of incident character for each loss control report sorted by the type of incident, organization and severity for the period from January 1, 1990 through December 31, 1999. A total of 14,407 incident characters were recorded. 'A' refers to actual incidents while 'N' refers to near miss incidents.

Incident Character	Injury				Illness			
	Company		Contractors		Company		Contractors	
	A	N	A	N	A	N	A	N
n =	3122	3779	6052	1185	140	67	46	16
Struck by or Against	22	38	17	49	3	7	19	25
Caught on or Between	9	5	6	3	3	4	4	5
Exposure	7	10	4	6	26	39	13	40
Slip	8	7	4	5	1	0	0	0
Trip	2	6	1	3	0	1	0	5
Fall	6	10	2	9	1	0	0	0
Contact With	12	13	11	8	7	13	9	0
Overexertion	12	0	8	1	13	1	21	0
Foreign Body	10	2	15	6	2	5	2	0
Other	12	9	32	10	44	30	32	25

Table 2.7: The distribution (%) of body parts injured for each loss control report sorted by the type of incident, organization and severity for the period from January 1, 1990 through December 31, 1999. A total of 10,289 injured body parts were recorded. 'A' refers to actual incidents while 'N' refers to near miss incidents.

Body Part Injured	Injury				Illness			
	Company		Contractors		Company		Contractors	
	A	N	A	N	A	N	A	N
n =	3141	681	5959	349	116	5	33	5
Eyes	11	6	22	9	6	0	10	0
Head [a]	12	19	11	23	17	0	23	0
Fingers [b]	17	6	19	5	3	0	5	0
Hands [c]	9	9	11	8	9	20	18	20
Arms [d]	8	8	6	8	10	0	10	0
Back	12	9	9	9	9	0	3	0
Knees	5	7	4	5	1	0	0	0
Legs	6	8	4	7	4	0	3	0
Trunk [e]	7	13	6	14	10	0	8	0
Feet [f]	8	10	5	7	1	0	3	0
Internal	2	3	1	3	9	80	8	80
Other	3	2	2	2	21	0	9	0

a (includes face, neck); b (includes thumb); c (includes wrist); d (includes elbow); e (includes chest, hips, shoulders); f (includes toes, ankles)

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Table 2.8: The distribution (%) of nature of injury for each loss control report sorted by the type of incident, organization and severity for the period from January 1, 1990 through December 31, 1999. A total of 8,525 nature of injuries were recorded. 'A' refers to actual incidents while 'N' refers to near miss incidents.

Nature of Injury	Injury				Illness			
	Company		Contractors		Company		Contractors	
	A	N	A	N	A	N	A	N
n =	3137	660	4244	322	119	5	33	5
Cut	14	14	14	17	1	0	3	0
Fracture	2	11	1	9	0	0	0	0
Allergy	1	0	0	0	5	0	9	0
Sprain	19	14	16	15	9	17	11	17
Scrape	5	6	5	5	0	0	3	0
Shock	1	3	0	1	1	17	0	16
Welding Flash	1	1	1	0	0	0	0	0
Bruise	16	29	15	30	1	0	3	0
Crush	4	6	3	4	0	0	0	0
Foreign Body	11	6	21	6	2	16	6	17
Burn	8	2	8	3	2	0	3	0
Exposure	4	4	3	6	24	33	14	33
Puncture	2	2	2	1	2	0	0	0
Amputation	1	0	0	0	0	0	0	0
Dermatitis	1	0	0	0	4	0	9	0
Other	10	2	11	3	49	17	39	17

Table 2.9: The distribution (%) of basic cause for each loss control report sorted by the type of incident, organization and severity for the period from January 1, 1990 through December 31, 1999. A total of 4,122 basic causes were recorded. 'A' refers to actual incidents while 'N' refers to near miss incidents.

Basic Cause	Injury				Illness			
	Company		Contractors		Company		Contractors	
	A	N	A	N	A	N	A	N
n =	1092	1510	1044	382	46	20	23	5
Inadequate design	12	13	7	9	7	14	9	0
Low maintenance standards	5	6	3	5	3	5	0	0
Low work standard	17	25	25	26	7	19	15	25
Lack of knowledge or skill	10	9	10	12	8	0	9	25
Improper motivation	5	7	8	8	3	5	3	0
Worn out from normal use	4	8	2	5	0	5	0	0
Low purchasing standards	0	1	0	1	0	10	0	0
Overlooked by inspection	9	10	6	8	5	10	3	38
Physical problems	5	1	5	1	20	0	6	0
Insufficient planning	13	6	15	10	7	5	9	0
Other	20	14	19	15	40	27	46	12

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Table 2.10: The distribution (%) of substandard actions for each loss control report sorted by the type of incident, organization and severity for the period from January 1, 1990 through December 31, 1999. A total of 4,198 substandard actions were recorded. 'A' refers to actual incidents while 'N' refers to near miss incidents.

Substandard Actions	**Injury**				**Illness**			
	Company		**Contractors**		**Company**		**Contractors**	
	A	**N**	**A**	**N**	**A**	**N**	**A**	**N**
n =	1175	1194	1251	524	25	10	15	4
Operating without authority	0	1	0	1	0	0	0	0
Tampering / unauthorized removal	1	2	0	1	0	0	0	0
Unsafe position	20	10	18	11	10	8	6	0
Trying to gain or save time	11	11	9	12	10	0	6	0
Working unsafely on moving or dangerous equipment	1	3	2	2	3	0	6	0
Failure to warn or secure	4	11	5	9	3	23	11	20
Unsafe lifting or carrying	6	1	7	2	10	0	11	0
Inattentive to job hazards	41	33	44	35	26	38	33	20
Procedural Deviation	5	19	7	20	6	31	6	40
Other	11	9	8	7	32	0	21	20

Table 2.11: The distribution (%) of substandard conditions for each loss control report sorted by the type of incident, organization and severity for the period from January 1, 1990 through December 31, 1999. A total of 2,178 substandard actions were recorded. 'A' refers to actual incidents while 'N' refers to near miss incidents.

Substandard Conditions	**Injury**				**Illness**			
	Company		**Contractors**		**Company**		**Contractors**	
	A	**N**	**A**	**N**	**A**	**N**	**A**	**N**
n =	698	766	509	172	19	7	4	3
Inadequately guarded	11	14	13	12	0	12	0	0
Inadequate ventilation	2	2	3	1	17	13	17	40
Congested Area	23	11	25	15	9	13	33	0
Defective equipment, materials, tools	19	36	17	26	23	25	0	40
Inadequate illumination	4	2	4	2	0	0	0	0
Substandard housekeeping	10	15	10	17	4	0	17	0
Inadequate warning system	3	6	5	8	4	25	33	20
Other	28	14	23	19	43	12	0	0

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Table 2.12: The distribution (%) contributing factors for each loss control report sorted by the type of incident, organization and severity for the period from January 1, 1990 through December 31, 1999. A total of 1,425 contributing factors were recorded. 'A' refers to actual incidents while 'N' refers to near miss incidents.

Substandard Conditions	Injury				Illness			
	Company		Contractors		Company		Contractors	
	A	N	A	N	A	N	A	N
n =	555	317	428	100	15	4	5	1
Tried to avoid extra effort	27	35	33	28	13	25	17	0
Insufficient line-up/Follow-up by supervision	9	20	17	31	6	0	33	100
Exposed to extreme temperature	12	7	8	9	6	50	0	0
Other	52	38	42	32	75	25	50	0

Table 2.13: The distribution (%) work to control factors for each loss control report sorted by the type of incident, organization and severity for the period from January 1, 1990 through December 31, 1999. A total of 5,404 work to control factors were recorded. 'A' refers to actual incidents while 'N' refers to near miss incidents.

Work to Control	Injury				Illness			
	Company		Contractors		Company		Contractors	
	A	N	A	N	A	N	A	N
n =	192	433	2109	594	38	14	20	4
Training required	2	2	2	2	2	4	2	0
Instruct persons involved	29	18	24	29	31	13	24	21
Re-assign person(s) involved	1	0	1	0	3	0	5	0
Improve housekeeping	3	2	2	2	0	0	2	0
Require procedure revision	6	5	15	6	1	4	2	14
Inform department personnel	24	39	18	32	24	39	34	14
Improve compliance with standards	5	5	4	5	3	9	0	7
Repair, replace or provide equipment	11	13	5	8	8	13	5	21
Implement corrective action	1	1	1	3	0	0	2	0
Improve inspection	4	3	2	3	3	0	2	7
Improve design	5	3	7	3	10	1	13	2
Improve protective equipment	3	1	2	1	2	4	2	14
Improve rules and regulations	1	1	1	1	0	4	0	0
Other	5	5	16	5	13	9	7	0

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Chapter 3

Comparative Review of Occupational Injury and Illness Surveillance Data from Two Sources at a Mid-Sized Industrial Organization: A Case Study[1]

[1] This chapter is condensed from a technical report issued to Syncrude Canada Ltd. entitled: A Comprehensive Analysis of Occupational Injury and Illness Surveillance Data at Syncrude. AMELL, T.K. & KUMAR, S., submitted in September 2000.

3.1 Introduction

Occupational injuries and illnesses place a substantial burden on the industrial workforce. Aside from the direct effects of the injury or illness on the worker such as pain, suffering, limited usage of the affected body part, and unfortunately in some cases, disability, there are other factors such as work-team cohesion and psychosocial influences both at home and at work. It is well established that work-related injuries and illnesses account for a large portion of lost workdays in industry. According to Human Resources and Development Canada (HRDC), over 15 million work days in 1998 were lost due to injury or illness (HRDC, 2000). When an employee is injured or becomes ill, the cost of that injury or illness is not easily calculated due to a variety of factors. Aside from direct medical, indemnity and risk management costs associated with an injury or illness, there are also ancillary or indirect costs such as lost productivity; overtime associated with compensating for injured workers; work-site modification and/or supervision of injured workers, recruitment, and retraining of replacement workers, human resources department costs for managing injuries, and unfortunately, under certain circumstances, legal fees. Together, these factors combine to represent a significant opportunity for cost reduction since occupational injuries and illnesses are manageable and preventable.

However, if occupational injuries and illnesses are to be managed, controlled and prevented, an accurate accounting (surveillance) of the number of accidents of this nature is necessary, in addition to rudimentary and essential data pertaining to the injured worker, their job location, how the injury occurred, etc. With a sound comprehension of

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this information, injury management and prevention strategies can be successfully implemented.

In order to be effective, surveillance of occupational injury and illness must be directly linked to preventative action (Baker & Matte 1992). Without this link, the entire process is without merit. Three levels of occupational injury and illness prevention are typically implemented. These include primary prevention, which is the control of workplace hazards (ergonomics) in which the condition does not occur. Secondary prevention is the detection (the surveillance system itself) and treatment of asymptomatic cases before symptoms occur. Tertiary prevention is preventing consequences of existing conditions or ensuring that recurrent conditions do not occur (workplace accommodation to an injured worker) (Hensrud 2000). Secondary prevention must support primary prevention efforts. The surveillance system should satisfy two requirements, it should:

1. Properly identify cases of occupational injury and illness
2. Monitor trends of occupational injury and illness

Proper case identification is required to target an intervention of direct value to the affected individual, and to others at risk of incurring the same injury or developing the same disorder (Baker & Matte 1992). Trends of occupational injury and illness may be used to assess variations in (1) different industrial groups, (2) different geographic areas and (3) different time periods. In order for this to occur a sound job classification system must exist, and meaningful geographical and/or functional location grouping information must be known.

Occupational injury and illness surveillance is an integral component of any Loss Management Program, and certainly the basis for any ergonomic strategy aimed at reducing the incidence and prevalence of Occupational injuries and illnesses at Syncrude. This holds true for all interventions and is not limited in scope to ergonomics as a reliable source of these data is paramount. Ideally, before any comprehensive ergonomic initiatives can be implemented, there must be a sound foundation of occupational injury and illness surveillance in place. This facilitates program evaluation and greatly improves the overall strength of the program; furthermore, with an accurate measure of the

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outcome, ineffective programs are more easily identified and altered to improve their effectiveness.

Surveillance exists in two sorts, those of passive and active means. Passive surveillance involves monitoring company records of injury reports (the Loss Control Reporting System in Syncrude's case), medical centre visits, Workers' Compensation Board (WCB) data etc. for the purpose of identifying areas of concern. It is a passive method of monitoring the health status of the workforce. On the contrary, active surveillance involves deliberate solicitation of information regarding a particular issue. Syncrude currently employs two methods of passive surveillance, the Corporate Loss Management Loss Control Reporting System (LCRS), as well as the Syncrude Medical Centre Occupational Health Database, currently referred to as Medgate (SMC).

The LCRS was described in great detail in Section 2.2.2 of Chapter 2. In summary, it is a custom-written, large computer database whereby data are stored and are capable of being sorted and manipulated in a variety of methods. The database is updated live throughout the corporation and an up-to-the-day count of accidents can be called up at any point in time. Unlike the SMC, the LCRS database contains information pertaining to all sources of loss (or potential loss) for the organization, and not just those resulting in occupational injury or illness. Data from the SMC were compiled in two forms; the more recent data were extracted from the Medgate Patient Information Database, beginning in 1999, as well as the old Microsoft Access Occupational Injury/Illness Database in use prior to 1999. The SMC database is currently not linked with the LCRS system.

Typically, an injured worker notifies her or his supervisor of an accidents, or series of accidents in the case of occupational illness or a suspected 'repetitive strain injury,' and proceeds to the SMC whereby they are assessed and treated if need be, and should the case be severe, they are sent to the Northern Lights Hospital or to a physician within the city Fort McMurray, Alberta. Rehabilitation services may also be utilized within the city. Occupational health nurses are responsible for the inputting and maintenance of the medical data in the SMC. Each day a list of occupational injury and illness related visits to the SMC is faxed to corporate and departmental loss management, and the accident is recorded, and opened for investigation from a loss management viewpoint. Should the Workers' Compensation Board of Alberta (WCB) become

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involved, this is handled by the health and wellness advisor for each respective operating division within the organization. The efficacy and efficiency of this process is the subject of the analysis reported herein.

The purpose of this case study was to compare the efficacy of the two methods of occupational injury and illness surveillance currently employed at Syncrude Canada Ltd. based upon the number of reported accidents resulting in occupational injury and illness.

3.1.1 The Industrial Organization: Syncrude Canada Ltd.

The mid-sized industrial organization drawn upon for example in this paper employs approximately 3600 full time workers and a varying number of contractors for an average total equivalent workforce of approximately 7,000 over the period from 1995 through 1999. The organization operates 24 hours per day, 7 days a week on a shift basis. The mandate of the organization is to produce a high-quality blend of synthetic oils that can be further upgraded and processed by other facilities into various petroleum products such as gasoline, jet fuel, plastics etc. Workers perform a variety of tasks, including tasks specific to open-pit surface mining, heavy machinery operation and maintenance, refinery process control, and maintenance as well as administration.

3.2 Methods

3.2.1 Comparison of Surveillance Data

Data were extracted from the loss control reporting system (LCRS) employed by Syncrude Canada Ltd. for the five-year period ending on December 31, 1999. A second set of data were originally solicited for this same time period from the Syncrude medical centre (SMC) occupational injury and illness database. Unfortunately, only four years of data were available from the SMC, and as a result only the years 1996 though 1999 were incorporated into the analysis. Data were analyzed in terms of the number of raw accidents, as this was the most appropriate method of comparing surveillance system output. The definitions for

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'injury' and 'illness' used in this case study are listed in section 3.7.

Raw accident data used in the comparison were categorized by organization (Syncrude Canada Ltd. Employees or Contractor), type of accident reported (injury or illness) and by the accident descriptors of 'injured body part' (e.g., eye), and 'nature of injury' (e.g., cut and puncture). Although other accident descriptors were available, only mutual descriptors used by both the LCRS, and the SMC could be analyzed. In addition, a conversion was necessary in order to compare the output of the respective systems. Table 3.1 lists the respective descriptors used in the conversion process of SMC data into corresponding LCRS categories for the injured body part and the nature of injury.

With respect to the nature of injury descriptors in table 3.1, several minor differences were adjusted for in the analysis. Since no corresponding SMC variable exists for the LCRS variables of 'allergy,' 'shock,' and 'dermatitis', for the purpose of comparison, and so as few data points as possible are lost during the analysis, these variables were merged with the 'other' nature of injuries in the LCRS (table 3.1). The LCRS 'scrape' descriptor was combined with 'bruise' because the corresponding category of 'abrasion/contusion' is used in the SMC system. The LCRS variable of 'puncture' was combined with the 'cut' due to the similarities between the two categories; they both involve breaking the integrity of the integumentary system. A category for 'no injury' was also added into table 3.1 in order to avoid 'no injury' SMC data from being compared to LCRS data.

Two additional and important differences exist with respect to the nature of injury captured by the SMC (table 3.1). Repetitive motion is recorded as a nature of injury in the SMC, but not in the LCRS. For this reason, repetitive motion injures, as noted by the SMC, are combined with strain/sprain injuries due to the similarities of their etiology. Repetitive motion injuries reported by the SMC have increased substantially over the 4-year period ending in December 1999, as described in Table 3.2 which lists the relative contribution of repetitive motion to the SCL data. Adjunct to repetitive motion injuries, foreign body injuries are also categorized differently by the SMC. The SMC divides the foreign body nature of injury into two groups, those that affect the eye, and those that do not. This in contrast to the LCRS, which does not make this distinction at this level. Although these data exist at a deeper level in the data, it is helpful to know how many of

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these accidents affect the eye in a 'top-level' analysis such as is found in this case study. Included in table 3.2 is information concerning the relative contribution of foreign body injuries to the eye in the SMC database. It is evident from table 3.2 that a substantial number (90%) of all foreign body injury visits to the SMC involve the eye.

3.2.2 Assumptions and Limitations of Passive Surveillance Data

Assumptions were made when analyzing the data contained herein. The loss control reporting system was used as the measure of choice, against which all other data were compared. Therefore, it was assumed that these data were the most accurate account of occupational injuries and illnesses available at Syncrude. In order to carry out this comparison, re-classification was necessary in some instances, as noted above. Furthermore, it was assumed that there were no duplicate entries in the data, and that they were correctly classified at the time of data entry or subsequently re-classified prior to the data capture for this analysis, which took place in March 2000.

3.3 Results

Table 3.3 lists the occupational injury and illness data for the five-year period beginning January 1 1995, and ending December 31 1999. There is a general upward trend with respect to occupational injury reporting by contractors, while the number of accidents involving Syncrude Canada Ltd. employees (SCL) remained relatively stable during this period. Contractors report far more injuries than SCL employees. Occupational illnesses account for fewer accidents reports than injuries. Accident counts for SCL employees are typically greater than for contractors, and are also relatively stable in frequency. Conversely, accident counts for contractors are increasing in frequency, as was found for injuries. From the SCL data in Table 3.3, it is evident that accidents resulting in occupational injuries increased by approximately 10% per year between in 1996 and 1998, and then decreased substantially in 1999 to 1995 levels. The contractor data in table 3.3 reveals a different trend. Injury reports increased over 97% in 1997, remained relatively stable in 1998 and increased over 68% in 1999, thus the overall

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difference between the 1999 and 1995 number of reports was over 230%. Occupational illnesses follow a similar trend. For SCL employees, over the five-year period examined, there was no difference between the numbers of reported accidents; however there was a slight increase between 1996 and 1998, followed by a 25% decrease in 1999. With respect to the contractor data, the number of reported accidents is highly variable, although with such few reports, 1 or 2 accidents can profoundly affect the data. Overall, there was an increase of over 166% in the number of reported occupational illnesses by contractors in this time period.

Table 3.4 lists the overall comparison of occupational injuries and illnesses between the two surveillance systems for SCL employees and contractors. Since the SMC database does not discriminate between injuries and illnesses, the values extracted from the LCRS are combined for the purpose of comparison. Over the four-year period, there is less than 1% difference between the total number of recorded accidents for SCL employees by the two systems. Unfortunately there was considerable variance on a year by year basis with the SMC reporting 56% fewer accidents than the LCRS for the year 1996, while it reported 35% more accidents than the LCRS for the year 1999. Contractor data are less encouraging as the total number of accidents reported by this group to the SMC was 32% greater over the four-year period. Year by year comparisons revealed that in 1998 the SMC reported 100% more accidents than the LCRS while reporting 2% fewer accidents in 1999. One factor that could have affected the 1999 contractor SMC data is the exclusion of accidents involving this group from the SMC database from a new operating area of the organization. It is uncertain how many accidents fall within this category, however if 2% of the total number of accidents fall within this category, one could assume that the two reporting systems are in agreement in this respect.

Table 3.5 lists the comparisons for each injured body part as well as the nature of the injury. Some artificial differences between the two reporting systems may be due to the conversion process outlined in table 3.1, however, those differences noted in table 3.4, as well as for any variable, be it injured body part or nature of injury that was not converted as listed in table 3.1, are genuine.

The total number of eye injuries reported in this time period differs by 14% with the SMC reporting more accidents than the LCRS. The values range by as much as 68%

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difference between the two systems for accidents involving SCL employees in 1996 while as little as less than 1% difference for accidents involving contractors in 1999.

The total number of head injuries over the four-year period differed by over 6%, with large year by year variance. Interestingly, the number of injuries to the hands and fingers reported by each system, despite being combined for the purpose of analysis, only differ by 1.9%. There was large variation in year by year accidents counts for accidents involving the arms. In 1996, the SMC reported 78% fewer accidents than the LCRS for SCL employees; however it reported 62% more accidents for contractors. Overall, the total difference over the four-year period examined was less than 20%.

The two surveillance systems differ notably in their report of the number of back injuries on a year by year basis, ranging from an under-reporting of 51% for injuries involving SCL employees in 1996 to an over reporting of 51% for injuries involving contractors in 1997. Overall, there was a 5% difference between the two systems with respect to the back over the four-year period examined. For the knee, there was less than 4% total variation between the two systems for the four-year period examined. However, there were large year by year variances, ranging from as much as 75% under reporting by the SMC in 1996 to 0% difference in 1998 for accidents involving contractors.

The number of accidents involving the legs once again displays large year by year variance, with a 10% difference between the two systems in the total number of accidents reported for the four-year period examined. The number of injuries and illnesses involving the trunk differ dramatically depending on which data set is referenced. Overall, 54% fewer accidents were reported by the SMC, with the SMC database consistently reported fewer incidents than the LCRS. Since accidents involving the trunk were subject to conversions, these data may not be reflective of the true nature of this relationship. The number of injuries involving the feet as reported by the SMC differs by as much as 75% from the LCRS, with an overall difference over the four-year period studied of 6%. There are large year by year variances amoung the number of accidents involving the internal organs. The number of other body parts noted as the site of injury by the SMC is 161% greater than that reported by the LCRS. However, since numerous conversions were necessary, these data may be reporting artificial differences.

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Injuries of the cut and puncture nature differed notably depending on which surveillance reporting system was queried. Since cut and punctures were combined in the LCRS data, this may have inflated the values and hence may account for some of the difference. The number of fractures reported by the surveillance systems differ remarkably, with the LCRS reporting 13% more fractures that the SMC. Large year by year comparisons range from as much as 83% to 0% difference. Since no conversion was necessary for this variable, this finding is quite disquieting.

Interestingly, with the exception of 1996 data for SCL employees, the SMC consistently reported more sprains than the LCRS, with an overall difference in reporting of 47%. Injuries attributed to welding flashes were substantially affected by year by year variations, however when examined over the four-year period, only a 7% discrepancy was revealed. Injuries of the bruise and scrape variety, differed by over 28% depending on which surveillance reporting system was queried.

The SMC appears to over-report the number of crush injuries based upon LCRS data. There was large year by year variance, and an overall difference of over 23% between the two systems over the four-year period examined. Since no conversion was necessary for these data, confidence may be placed in this value.

Overall, the number of foreign body injuries reported by each respective surveillance system is was less than 9%. However, there was large variation based on year by year comparisons. The data for the year 1999 seem to show less of a difference over the 1996 and 1997 data when the greatest differences were reported.

Injuries of the burn variety differed by only 2% overall. However, the values for SCL employees differ by up to 82% depending on which year is examined. The overall number of exposure accidents, as reported by each system exhibited marginal agreement, however once again was affected by rather profound year by year variation.

Although very severe in nature, the two surveillance systems report different numbers of amputations over the four-year period examined. Since there were very few such injuries occurred, the percentage discrepancy between the two systems is exaggerated, and nevertheless, they do report varying numbers of accidents.

Naturally, some minor discrepancies between the two surveillance systems is expected due to the conversion process outlined in table 3.1. However, the conversion

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was designed such that minimal impact on the overall integrity the data would have ensued while obtaining maximal retention of the data. Furthermore, since a discrepancy between the LCRS and the SMC data did exist for the overall numbers presented in Table 3.4, confidence may be placed in these data, and there is in fact a difference between the two reporting systems with respect to reported accidents of occupational injuries and illnesses. Even when the data pertaining to the organization of the injured worker (contractor or Syncrude Canada Ltd. employee) are removed, and raw data are input, there exists a difference over the four-year period examined. Over this period, the LCRS reports that 1248 injuries (and illnesses) were incurred by SCL employees and 3180 injuries (and illnesses) were incurred by contractors. Over this same period, the SMC reports that 1260 injuries were incurred by SCL employees while 4219 injuries were incurred by contractors. Taking this into account, the following equation may be used to derive to total discrepancy between the two reporting systems:

$$\frac{(\text{LCRS}\,1248+3180)-(\text{SMC}\,4219+1260)}{(\text{LCRS}\,1248+3180)}X100\% = 23\%$$

Thus over all there was a total discrepancy of over 23% between the two systems, with the SMC reporting more accidents than the LCRS.

Those injured body parts and nature of injury descriptors where no conversion was necessary (eyes 14%, knees 4%, fractures 13%, welding flashes 8%, crushes 23%, burns 2%, exposures 6% and amputations 29%) also act as a measure of discrepancy. These variables typically express less variance than those variables which necessitated a conversion in order to be admissible in the comparison (table 3.5).

Since only injury and illness accident counts could be analyzed directly, and these counts are susceptible to variations in the workforce characteristics, ancillary information in the form of injury frequency rates are provided in table 3.6. Overall, the rate of recordable injuries is greater than that of both medical aid injuries and disabling injuries. The recordable injury rate for SCL employees over the five-year period is 40% that of contractors, while the medical aid and disabling injury rates are 37% and 86% respectively. Thus, contractors are more likely to report accidents of the recordable injury and medical aid type, and equally likely to report disabling injuries.

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3.4 Discussion

Overall, there was a large difference (23%) between the number of reported accidents recorded by the LCRS and the SMC. However, this value may be marginally inflated due to the fact that accidents occurring at the newly commissioned operating area of the organization during 1999 were not captured by the SMC database, as indicated by the –2% value for 1999 in table 3.4. Aside from large year by year variation in the number of accidents reported by each respective system, there were differences between the overall numbers of accidents during the four-year period examined.

Regardless of which surveillance system is used as the basis for monitoring the injury trends at Syncrude over the past four or five years, one fact remains indisputable, that is that the number of occupational injuries to Syncrude Canada Ltd. employees and contractors has increased substantially. The number of occupational injuries reported by the LCRS has increased approximately 2% in SCL employees and over 230% for contractors during the period from 1995-1999. The number of occupational injuries reported by the SMC for these two groups has increased 186% and 147% respectively for the years 1996-1999. The number of occupational illnesses, although minimal in comparison to occupational injuries, has remained stable in SCL employees and increased 166% in contractors according to LCRS data.

These values increased, with the exception of occupational illnesses in SCL employees despite a 6% decrease in the total number of SCL employees from 1995-1999 and a 9% decrease in the total number of hours worked by SCL employees. There was an increase in the recordable injury frequency rate as well as the medical aid injury and disabling injury frequency rate during the period from 1995 to 1999, however these values have declined after large increases in 1996, 1997 and 1998. Contrary to this, an 85% increase in the number of contractors was accompanied by a staggering 230% increase in occupational injuries. This increase in workforce was accompanied by an 81% increase in the total number of hours worked by contractors during this time period. Interestingly, the recordable injury frequency rate as well as the medical aid injury and disabling injury frequency rate for contractors decreased during the period from 1995 to 1999. Therefore, despite increases in the workforce and correspondingly, the number of

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hours worked, as well as the overall number of accidents, there was a decrease in the rate of injury. One additional factor that affects these results is that the year used for the basis of comparison for the longitudinal rates over the five-year period, all obtained from the LCRS, was 1995. During this year, Syncrude Canada Ltd. obtained the lowest recordable injury frequency rate during the past 10 years for both SCL employees and contractors. Thus, since the comparisons contained herein are construed with respect to such a low value, even values representing a large decrease over values obtained in 1996, 1997 or 1998 are in fact higher than 1995 values.

Furthermore, since the number of SCL workers has decreased, and presumably the same level of productivity has been maintained, or perhaps even greater productivity has been achieved, the accompanying increased workload spread over a smaller workforce could potentially result in a decrease in the amount of time devoted to concentrating on occupational health and safety.

In terms of the overall loss management perspective, the most frequently recorded type of accident with respect to contractors are occupational injuries, eclipsing all other Loss Management variables with the exception of 'damages', however still accounting for over 50% of all accidents. This clearly indicates that extensive efforts are needed to promote safe work practices among contractors. An integral companion to safe work practices is job design requirements, a task suitable for the implementation of ergonomic principles.

The method of choice for comparing the surveillance data is the single greatest limitation of this analysis. However, it was the most appropriate method of answering one of the questions at hand, which was whether or not the two surveillance systems in place at Syncrude Canada Ltd. are in agreement with respect to the numbers and types of occupational injuries and illnesses reported by SCL employees and contractors. Using raw injury and illness data from both the Syncrude Loss Management Reporting System (LCRS) and the Syncrude Medical Centre Medgate Patient Information Database (SMC) required several conversions in order to allow for a meaningful comparison in certain instances. Those instances that did not require a conversion were found to be a suitable measure of the accuracy of this method.

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The comparisons noted reveal that the two surveillance systems do not report concurrent findings. Some differences were notably attributed to the conversion process necessitated by the uncommon language and classification utilized by the two systems. Where no conversion was necessary a discrepancy was also revealed. Even when the organization (SCL employee or contractor) strata were removed, the two systems differed by over 23%. The conversions made at the lower strata levels (injured body part, nature of injury) affected the comparison data, however these were accounted for in terms of those factors not converted and hence there was indeed a difference. This result emphasizes the need of a common language throughout Syncrude's departments responsible for monitoring these events such that these sorts of discrepancies do not occur.

The analysis contained within this report does not reveal why the two systems yield different values. The Medgate system currently in use by the SMC is a much more thorough and comprehensive patient management system than the older databases used by the SMC in the past. Over time this system should increase the reliability and validity of occupational injury and illness reporting from the SMC data. However, other factors may also have contributed to the discrepancies such as data entry issues and coding strategies. Utilizing a standardized coding structure throughout Syncrude's operations is the first step towards a concise, integrated surveillance system. Since the root cause(s) of the discrepancies are not known at this time, additional auditing of the complete injury reporting procedures at Syncrude are warranted, from the initial accident in the field right up until the accident is closed in the LCRS database.

The LCRS data concerning occupational injuries and illnesses are utilized by Syncrude as the 'gold standard' on which to base Loss Management decisions, develop and establish intervention and prevention strategies as well as monitor trends over time. As noted earlier, Syncrude Medical Centre data supplied to Loss Management are used as a daily account of accidents, and hence there exists a direct link between the two systems. Although the SMC data are not the primary method of surveying these accidents, they are utilized in the quarterly stewardship reports, and the LCRS is dependent upon SMC data. If the number and classification of these accidents are incorrect, as indicated by the overall 23% discrepancy between the two totals over the four-year period, then there is

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the distinct possibility of over- or under-reporting occupational injuries and illnesses at Syncrude. This over- or under-reporting of accidents could lead to erroneous managerial decisions based upon incorrect data. Since it is of the utmost importance that any decisions regarding injury management, control and prevention at Syncrude be based upon accurate, clear and timely information concerning occupational injuries and illnesses, any misinformed decisions could have a severe impact on Syncrude's efforts to minimize the occurrence of these accidents and ultimately affect Syncrude's goal of zero disabling injuries.

This finding underscores the need for a shared occupational injury and illness database between those departments concerned with this important aspect of operations at Syncrude. With such a shared component database, greater confidence may be placed within the data. Also, since it is also possible that many injuries go unreported to the Medical Centre to begin with, Syncrude can focus on improving this aspect of surveillance once the SMC and LCRS data report the same frequency, number and nature of accidents.

Another key factor is the notion of repetitive motion injuries (RMIs), which are classified by the SMC, but not addressed by the LCRS. Since RMIs typically have no single accident precipitating their onset, and are more gradual in nature, and typically the result of various ergonomic factors, their inclusion into the LCRS classification system is of great importance. This would enable Syncrude the ability to discern between a sprain due to a fall or another acute accident and a repetitive motion injury.

Although the LCRS is an excellent tool and forms the basis of a comprehensive loss management program, it does have limitations and these limitations must be eliminated in order to improve the surveillance capability of the system. With increased sensitivity and accuracy of the information contained in the LCRS, intervention and prevention strategies employed by Loss Management aimed at controlling occupational injuries and illnesses have a greater likelihood of success. This case study revealed that the two separate systems as they exist today are not in agreement and hence may contravene the improvement efforts of the organization targeted at reducing the frequency and severity of occupational injury and illness since an accurate accounting process is not in place.

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3.5 Specific Recommendations to Improve Surveillance

1. Additional analyses are required concerning the occupational injury and illness reporting procedures followed in the field. Employees must continue to be encouraged to report all injuries and illnesses immediately to their supervisor, to the Syncrude Medical Centre as well as the area loss management representative, without fear of repercussion. Detailed logs should be kept and collected for analysis and quality assurance through comparison to both Syncrude Medical Centre and Loss Management data sources. The injury and illness reporting process must be audited and then streamlined to reduce redundancies and improve operational reliability. Standardized procedures should continue to be employed by the Syncrude Medical Centre personnel regarding the recording of accidents with respect to the completeness of information and consistent categorization of injuries and illnesses.
2. A common, standardized injury and illness classification system must be employed by all Syncrude at all levels. This will greatly enhance the transfer of information between the two principal surveillance systems. The adopted classification system should also be easily compatible with that employed by the WCB of Alberta in order to ensure simple comparisons of Syncrude's health status and that of the sub-sector, sector, province and nation in the future. A modification of the International Classification of Disease (ICD-9CM, 1992) could easily be implemented and standardized conversion tables be created in order to ensure easy comparison and effective surveillance.

The classifications used by the LCRS should be modified to include Repetitive Motion Injuries (repetitive strain injuries; cumulative trauma disorders). This nature of injury has been described by Health Canada and the WCB as one of the most commonly occurring work-related conditions. According to the Syncrude Medical Centre data, Repetitive Motion Injuries have increased substantially in frequency over the past four years, and unfortunately, as noted in below, the Loss Control Reporting System is not designed to accommodate these injuries and illnesses. They must be addressed. Although they still appear to account for less than other types of injuries, these accidents should not

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be amalgamated with other variables but should stand alone to enhance the chances of success in their control.

Furthermore, the frequency of this type of injury, and several others has been shown to be reduced by interventions based upon ergonomic and human factors based principles. However, without accurate information concerning these injuries, the most appropriate location, work-group or job task in which to implement these interventions and preventative efforts would not be known.

3. The utilization of a common information source would greatly simplify reporting, managing and controlling the occupational injuries and illnesses at Syncrude. This would require the integration of the two surveillance systems currently in place at Syncrude at the database level, using Syncrude's existing data warehouse. The integration of the two surveillance systems is of necessity following the auditing of the injury recording process procedures outlined in recommendation 3 that should identify any other possible factors contributing to the discordance between the two systems illustrated in this analysis. A shared database would strengthen the information concerning each accident from a Loss Management and future prevention/control perspectives and not increase the workload of those in the Medical Centre responsible for inputting the accidents into the database. This shared database could contain all the pertinent information from the Loss Management perspective, Syncrude Medical Centre perspective as well as the Human Resources perspective. Only data relevant to each department would be accessible by that department, with no department controlling all aspects of the database. This would ensure the confidentiality of each worker. It is our understanding that Syncrude was investigating the possibility of such a database in 1999; the data presented herein wholly support the need for such a shared database. The redundancy and possibility of error associated with each level of redundancy would be greatly reduced, ultimately procuring a comprehensive, robust occupational injury and illness surveillance system capable of guiding Syncrude's injury control efforts for the foreseeable future.

For example, upon the reporting of an initial injury or illness to the Syncrude Medical Centre, an accident reference number would be given to the injured worker, and the relevant patient demographic information (name, age, sex, job title, job location etc.) as well as information regarding the complaint (nature of injury, body part injured,

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diagnosis, referral to a physician within Fort McMurray, rehabilitation, WCB etc.) as well as medical history (recurring problem, back pain, smoking habits etc.) data would be input into the system. Any future injuries would be assigned a different accident reference number and all common accident reference numbers would be associated with the appropriate employee ID within the database. This information may then be used to compliment a comprehensive Loss Management based account of the accident, including issues such as Incident Character and relation of the injury to the job task the worker was performing when she/he became injured etc., leading to an accurate account of the root cause of the accident.

This information can be monitored from various perspective as well as time frames, and ultimately contribute a great deal to reducing the impact of occupational injuries and illnesses at Syncrude.

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Table 3.1: Categories used in the conversion of Syncrude Medical Centre (SMC) data into a format compatible with Loss Management Data (LCRS) for the injured body part and nature of injury.

Injured Body Part		***Nature of Injury***	
LCRS	**SMC**	**LCRS**	**SMC**
Eyes	Eyes	**Cut**	Laceration/Wound
Head	Head; Neck; Ears; Face	**Fracture**	Fracture/Dislocation
Fingers [a]		**Allergy** [b]	
Hands	Hands/Wrists/Fingers [a]	**Sprain**	Strain/Sprain; Repetitive Motion
Arms	Shoulders/Arms	**Scrape** [c]	
Back	Back	**Shock** [b]	
Knees	Knees	**Welding Flash**	Welding Flash
Legs	Legs/Hips	**Bruise**	Abrasion/Contusion
Trunk	Chest; Abdomen;	**Crush**	Crush Injury
Feet	Feet/Ankle/Toes	**Foreign Body**	Foreign Body - Eye; Foreign Body – Other
Internal	Internal	**Burn**	Burns
Other	Multiple Body Areas	**Exposure**	Exposure
		Puncture [c]	
		Amputation	Amputation
		Dermatitis [b]	
		Other	Head/Internal Injury; Hernia; Other Illness/Injury; Inhalation; WCB Reportable Hearing Loss;
		No Injury	No Injury Noted [b]

a = SMC data differs from the LCRS at this point, SMC combines finger data with the hand and wrist while the LCRS separates the fingers from the hand.; b = No corresponding SMC variable exists for this LCRS variable. Allergy, Shock and Dermatitis were combined with Other; c = These LCRS variables were combined with a similar Nature of Injury for purpose of comparison. Scrape was combined with Bruise and Puncture with Cut.

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Table 3.2: Contribution of repetitive motion injuries to the total number of sprain/strain nature of injuries and foreign body eye injuries to the total number of foreign body injuries in Syncrude Medical Centre (SMC) data, 1996-1999. Numbers in parenthesis indicate percentage contribution.

Nature of Injury	1996	1997	1998	1999
Repetitive motion injuries				
SCL	2	9	24	16
Contractors	4	6	5	17
Total	6	15	29	33
Sprain/Strain Injuries				
SCL	48 (4%)	118 (8%)	146 (6%)	130 (12%)
Contractors	94 (4%)	192 (3%)	220 (2%)	334 (5%)
Total	**142 (4%)**	**310 (5%)**	**366 (8%)**	**464 (7%)**
Foreign Body Eye Injuries				
SCL	8	33	29	33
Contractors	107	214	204	204
Total	115	247	233	237
Foreign Body Total Injuries				
SCL	10 (80%)	39 (85%)	40 (73%)	38 (87%)
Contractors	117 (92%)	234 (91%)	233 (86%)	224 (91%)
Total	**127 (90%)**	**273 (90%)**	**273 (86%)**	**262 (90%)**

Table 3.3: Accident count for occupational injuries and illnesses based upon LCRS data, 1995-1999.

Accident Count	1995	1996	1997	1998	1999	1995-1999
Injuries						
SCL Employees	253	281	307	334	258	1433
% Difference on a yearly basis	/	11	9	8	-22	**2**
Contractors	369	401	792	727	1222	3511
% Difference on a yearly basis	/	8	97	-8	68	**231**
Illnesses						
SCL Employees	15	16	17	20	15	83
% Difference on a yearly basis	/	6	6	17	-25	**0**
Contractors	6	6	8	8	16	44
% Difference on a yearly basis	/	0	33	0	100	**166**

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Table 3.4: Overall comparison of total number of accidents for the period 1996-1999 as reported by the LCRS and the SMC. Values for the LCRS consist of combined injury and illness data.

Source	Type of Accident	1996	1997	1998	1999	1996-1999
LCRS						
SCL Employees	**Injuries**	281	307	334	258	1180
SCL Employees	**Illnesses**	16	17	20	15	68
Total		297	324	354	273	1248
SMC		129	373	389	369	1260
% Difference of LCRS		**-57**	**15**	**10**	**35**	**1**
LCRS						
Contractors	**Injuries**	401	792	727	1222	3142
Contractors	**Illnesses**	6	8	8	16	38
Total		407	800	735	1238	3180
SMC		489	1038	1483	1209	4219
% Difference of LCRS		**20**	**30**	**102**	**-2**	**33**

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Table 3.5: Comparison of LCRS and SMC accident counts for accidents involving injured body part and nature of injury. 1996-1999. SCL = Syncrude Canada Ltd. employee; CON = Contractor.

Descriptor	1996		1997		1998		1999		
	SCL	CON	SCL	CON	SCL	CON	SCL	CON	Total
Body Part									
Eyes	-69	25	11	34	-14	28	23	-1	**14**
Head	-48	21	10	8	-28	17	-9	-20	**-6**
Hands	-629	-69	-109	10	39	12	15	-7	**-2**
Arms	-78	62	3	33	37	55	42	-10	
Back	-51	24	15	51	-6	38	-18	-29	**-5**
Knees	-75	-10	7	22	-12	0	11	-4	**-4**
Legs	-75	76	19	54	9	45	16	-11	**10**
Trunk	-83	-28	-64	-48	-28	-52	-72	-63	**-54**
Feet	-76	0	-12	19	-13	62	5	-25	**-6**
Internal	0	0	-10	25	-17	8	400	418	**81**
Other	-36	23	75	430	433	193	1400	123	**161**
Nature of Injury									
Cut and Puncture	-61	-18	-26	-16	-32	-2	4	-25	**-21**
Fracture	-83	58	-33	44	0	-10	0	-62	**-13**
Sprain	-26	114	60	67	22	56	81	41	**48**
Welding Flash	/	50	0	55	-33	0	/	-25	**8**
Bruise and Scrape	-76	-18	-56	-12	-41	-9	2	-32	**-29**
Crush	-37	25	50	15	7	43	20	27	**23**
Foreign Body	-67	28	25	19	-9	27	-7	-7	**9**
Burn	-82	5	-18	14	-3	16	-8	-11	**-2**
Exposure	-66	15	-54	31	-7	0	90	95	**5**
Amputation	/	0	-100	0	0	0	-100	0	**-28**
Other	-75	-25	-17	-10	-18	-4	-47	-48	**-33**

Table 3.6: Frequency rates for recordable injuries, medical aids and disabling injuries for SCL employees and Contractors, 1995-1999. Based upon the number of injuries per 100,000 hours worked.

Source of Rate	1995	1996	1997	1998	1999	$\overline{X}$
SCL Recordable Injury Frequency Rate	0.62	0.80	0.91	0.94	0.77	**0.808**
Medical Aid Injury Frequency Rate	0.47	0.44	0.58	0.86	0.65	**0.600**
Disabling Injury Frequency Rate	0.16	0.36	0.33	0.08	0.41	**0.268**
CON Recordable Injury Frequency Rate	2.38	1.42	2.33	1.70	1.81	**1.929**
Medical Aid Injury Frequency Rate	2.00	1.26	1.92	1.43	1.46	**1.614**
Disabling Injury Frequency Rate	0.38	0.16	0.41	0.26	0.34	**0.310**
Combined Recordable Injury Frequency Rate	1.19	1.01	1.55	1.26	1.28	**1.258**
Medical Aid Injury Frequency Rate	0.96	0.72	1.18	1.10	1.06	**1.004**
Disabling Injury Frequency Rate	0.23	0.29	0.37	0.16	0.23	**0.256**

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3.7 Definitions

Injury (Occupational)

Any injury, such as a cut, fracture, sprain, amputation, etc., which results from a work-related accident or exposure involving a single incident in the work environment. Adapted from: 'Standards for Injury/Illness Recordability' Syncrude Canada Ltd. January 1991.

Illness (Occupational)

Any abnormal condition or disorder of an employee, other than one resulting from an occupational injury, caused by exposure to environmental factors associated with employment. Occupational illnesses include illnesses or diseases caused by inhalation,

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absorption, ingestion or direct contact with contaminants. Adapted from: 'Standards for Injury/Illness Recordability' Syncrude Canada Ltd. January 1991.

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Chapter 4

A Systematic Review of Literature Concerning Industrial Handwheel Actuation and the Human Operator[1]

[1] This chapter has been published in its present format. AMELL, T.K. & KUMAR, S. (2001). Industrial Handwheel Actuation and the Human Operator. A Review. *International Journal of Industrial Ergonomics.* 28(5), 291-302.

4.1 Introduction

Actuation of handwheels is a task common to numerous industries. Process plants in the petroleum, chemical and waste industries as well power generation utilize handwheels actuated by human operators to regulate the flow of material within a valve system (Wood *et al.*, 1999/2000; Schulze *et al.,* 1997a). Handwheels are also used in the railway industry as a means of regulating the movement of rail cars (Woldstad *et al.*, 1995) as well as in vehicle steering mechanisms (Wood *et al.*, 1999/2000; Sanders, 1981). Handwheels are the preferred control devices in systems when high torque levels are required, two hands are available to exert them, the turning rates are low and when accurate or partial turns are of necessity (Woldstad *et al*,. 1995; Sanders & McCormick, 1993; Woodson *et al.*, 1992; Eastman Kodak Company, 1983). Handwheels are commonly found as control devices for valves, and it has been estimated that 50% of all valves currently in use are operated manually (Shih *et al.*, 1997). According to McCormick (1976), the design of such control devices significantly affects the ability of the operator to actuate the device; even well engineered systems will perform ineffectually if controls are not adequately designed for human use (Raouf *et al.*, 1984; McCormick 1976).

Unfortunately, the job task requirement of industrial handwheel actuation frequently exceeds the safe work capability of the human operator. For example, the minimum valve handwheel 'cracking' or 'breaking' force recorded *in situ* using a torque wrench for 336 valves of various handwheel diameters and heights at a large petroleum refinery was 100 Nm, while the maximum was 225 Nm (Parks & Schulze, 1998). The 'cracking' force is the force required to turn the valve handwheel from a locked position

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to an unlocked position for operation, it ends at the initial movement of the handwheel. A gross discrepancy results when these *in situ* values are compared with the empirically derived maximum torque production capabilities of operators recorded using handwheels of various sizes, heights, angles and distances from operators (Wood *et al.*, 1999/2000; Schulze *et al.*, 1997a & 1997b). The maximum torque produced by the operators reported in these studies was 62 Nm, significantly less than the lowest force required to actuate a valve *in situ*. Similarly, Jackson *et al.* (1992) reported that an operational torque of over 400 Nm was required to 'crack' 93% of 217 valves examined at a chemical plant.

In order to overcome the discrepancy between the task demand and the physiological capacity of the worker, operators frequently employ 'cheater bars' or valve wrenches to increase the lever arm and improve the coupling factor whenever possible while actuating handwheels. (Figure 4.1) Such a procedure is not always possible due to constricted workspaces or handwheel orientation. Furthermore, equipment damage may ensue as a result of this practice due to the fact that these tools can easily exceed the required amount of force to actuate the handwheel (Wood *et al.*, 1999/2000). As expected, the lack of consideration for human operator work capacity by the designers of such valve handwheel systems results in high injury rates reported by process operators. Process operators are those individuals in process plants whose job tasks primarily involve the actuation of industrial valve handwheels (Parks & Schulze, 1998). Parks and Schulze (1998) reported that 56% of low back injuries and 75% of head, neck and face injuries over a three-year period reported by process operators at a large corporation were attributed to industrial valve handwheel actuation. In addition to these data, a recently administered musculoskeletal discomfort questionnaire revealed that 88% of process operators at a large petroleum refinery reported musculoskeletal discomfort that they believed to be attributable to their job, and that industrial valve handwheel actuation was the most physically demanding task they were required to perform (Amell, 2000). These results are in complete accordance with those reported by Jackson *et al.* (1992) who state that valve 'cracking' was the most physically demanding task operators at a chemical plant were required to perform.

Factors contributing to the excessive task demands include: 1) the high torque required to 'crack' or 'break' industrial valves; 2) the continuous muscular effort required

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to fully actuate the handwheel (Jackson *et al.*, 1992); 3) handwheel diameter; 4) handwheel rim shape; 5) handwheel orientation relative to the operator (height above grade, pitch angle, distance from operator), and 6) handwheel environment (the lack of optimal and stable footing or bracing and the presence of obstructions) (Wood *et al.*, 1999/2000; McMulkin & Woldstad, 1995; Woldstad *et al.*, 1995). The high force required to 'crack' the valve handwheels is frequently greater than that required to actuate the handwheel to the stem limits (fully open or fully closed valve system), after it has been 'cracked.' The continuous muscular effort and aerobic capacity required to perform between 5 and 15 minutes of work may be greater in terms of absolute physical and physiological demand than the initial 'cracking' torque demand (Jackson *et al.*, 1992). Examples of poor handwheel orientation include handwheels that are located above the shoulder or below the knee, this is particularly demanding under continuous handwheel actuation requiring several minutes of aerobic effort in awkward postures. The pitch angle, distance from the operator and degree of freedom from obstructions in the workspace surrounding the handwheel all contribute to the awkwardness of the job task. Operators are frequently called upon to actuate handwheels that must be turned in confined spaces, often between pipe racks, all while reaching over another pipe or obstruction.

Flow resistance and in-line pressure in industrial valves may also contribute to the overall torque requirements while stem lubrication is also noted as a contributing factor (Parks & Schulze, 1998; Wood *et al.*, 1995). Safety issues such as the lack of railings and scaffolding, and environmental issues such as the ambient temperature and humidity may also contribute to the demand of the task, particularly in excessively cold or hot climates, or when handwheels are located proximal to high temperature or pressure vessels. The frequency of operation is also a factor, some valves may be required to be actuated yearly, or when a plant is brought offline, daily, or several times per shift in some plants. In certain instances, under emergency conditions, when a handwheel must be actuated quickly to avoid an incident or shut down a plant, psychological stress may also contribute to the demand of the task.

Unfortunately, there is little agreement among published research reports on acceptable ergonomic design guidelines for the task of industrial handwheel actuation.

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Furthermore, existing guidelines do not address numerous factors known to affect the operator's ability to safely complete the task. Several studies involving this specific task, as well as several involving related tasks are reviewed in this article.

The purpose of this article is to review the scientific literature concerning industrial handwheel actuation and the human operator, identify gaps in the knowledge and propose future research that will eventually lead to the adoption of industrial handwheel actuation tasks designed within the capacities and capabilities of the human operator.

4.2 Recommended Design Values

Information concerning industrial handwheel design has been discussed by several authors, including: Woodson *et al.*, (1992); the State Committee of the USSR, (1984); the Eastman Kodak Company, (1983); Van Cott & Kinkade, (1972) and Murrel, (1965). Tables 4.1 through 4.3 list the recommended design values by Murrel (1965), as cited by Woodson *et al.* (1992), the State Committee for Standards of the USSR (1984), as cited by Schulze *et al.* (1997a), and the Eastman Kodak Company (1983) respectively. In addition to the design values given by Murrel (1965), Woodson *et al.* (1992) also recommend that for both vertically and horizontally oriented handwheels, *strong* male adults can exert a maximum torque of 13.2 Nm given a handwheel diameter of 51 cm or greater.

From tables 4.1 through 4.3, it is evident that existing design recommendations are incomplete. Aside from the issue that the force requirements in the field significantly exceed the maximum design recommendations, there is a lack of consistency with respect to the force limit units, as table 4.1 limits are expressed in torques while tables 4.2 and 4.3 in tangential force. Although the tangential force is easily computed when the handwheel diameter is known, this may not always be the case. Handwheel diameter significantly affects the torque production capability of the operator regardless of the tangential force exerted. For example, assuming the operator applies a consistent maximal tangential force, the torque produced at the center of the handwheel is a direct function of the radius of the wheel, and hence handwheels with greater radii will produce

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greater torque than those with lesser radii when equal tangential forces are exerted. Future recommendations should include both the tangential force and torque production capabilities of the human operator.

Only those recommendations contained in table 4.1 consider the height from grade of the handwheel, if only for an extremely limited space envelope of 25 cm. None of the recommendations address both static isometric ('cracking') and continuous forces, nor do they consider footing and bracing, pitch angle, handwheel distance from the operator and the presence of obstructions, all commonly noted factors affecting the ability of operators to produce torque about a handwheel. Some of these issues have however been addressed under limited circumstances in the ergonomic literature involving industrial handwheel actuation and operator capabilities.

4.3 Review of Empirical Studies on Operator Capabilities

In light of the incomplete recommendations outlined above, several ergonomic studies on operator capabilities have attempted to address the shortcomings of existing guidelines for industrial handwheel actuation. These include four studies involving large handwheels and industrial valve systems, two studies involving large handwheels and railcar braking mechanisms, two studies using small handwheels and valves, three studies using industrial hand cranks and one study linking a novel large handwheel turning task, trunk posture and low back pain. Additional related articles involving vehicle steering wheel forces as well as the load on the low back while actuating a railcar breaking mechanism were also revealed by an extensive search of the literature.

Tables 4.4 and 4.5 list the relevant information, notes, and conclusions for those studies directly related to industrial handwheel actuation and those studies indirectly related to the task respectively. Although lacking in specific strength details concerning the capability of operators to exert isometric and continuous endurance efforts, the report by Jackson *et al.* (1992) yields very useful information concerning the correlation between strength and endurance as well as information regarding field work. This was the only study found in the literature that examined the role of endurance in continuous effort handwheel actuation. Of 51 subjects tested on the valve handwheel simulator, only 19

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(37%) completed 15 minutes of handwheel turning at a rate of 15 revolutions per minute (250 revolutions in total) and a power output of 1,413.5 foot-pounds/minute (1,908 Nm/minute). A power output of 1,908 Nm/minute was considered sufficient to close 75% of the emergency valves in the plant in 15 minutes or less (Jackson *et al.*, 1992). Of the 32 (63%) who did not complete the test, 20 (63%) halted due to fatigue before 4 minutes had elapsed, or before 60 revolutions had been completed.

Two studies similar in design published by Schulze *et al.* (1997a) and Wood *et al.* (1999/2000) reported similar results. In both instances, statistically significant main effects were reported for handwheel height above grade in relation to isokinetic torque, however post hoc tests failed to reveal the exact relationship between these variables. The difference between the heights in the former study was 41 cm and the latter 100 cm, with these values falling approximately between the knee and the shoulder levels of the average operator. Small sample size limits the ability of these studies to reliably detect differences between heights; furthermore, the range of heights of handwheels found in the field significantly exceeds these limits, rendering the applicability of these results to real-world facilities questionable (Parks & Schulze, 1998). The distance between the operator and the handwheel was investigated by Wood *et al.* (1999/2000), and was also found significant in respect to the main effects and not in the post hoc tests, however the two variables were only separated by 15 cm, a relatively small distance in terms of gross body dimensions; furthermore the same sample size limitations noted above are equally applicable.

In an interesting study of the 'cracking' forces required to actuate industrial valve handwheels in the field, Parks and Schulze (1998) reported that the handwheels located 50 cm above the grade, and over 200 cm above the grade required significantly more torque than all handwheels at heights in between. Thus, it seems that for those handwheels located within the maximum comfortable limits for human operation, between approximately 76 cm and 177 cm, based upon the reported heights, less torque is required than for handwheels located outside these limits. It is imperative that the safe force production capability of operators be established outside of this comfort range as designers may be, at least the plants studied (Parks & Schulze, 1998), designing tasks in opposition to established strength and endurance ergonomic axioms.

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In two well-designed and well-described studies, Woldstad and McMulkin (Woldstad *et al.*, 1995; McMulkin & Woldstad, 1995) defined population isometric capabilities for a vertically mounted handwheel turning task as well as examined the effects of handwheel rim design on tangential force production capabilities. The authors concluded that grip strength plays a significant role in tangential force production and that existing standard handwheel rim (typically smooth edged) shapes do not permit maximal force development. A zig-zag shaped rim permitted the production of 54% more force than the standard rim. Furthermore, the authors found that standard strength tests predicted tangential wheel strength very accurately (Woldstad *et al.*, 1995). Additional analysis related to this study in the form of an optimization-based biomechanical model of the task revealed that excessive compressive forces can focus at the L4/L5 intervertebral disc level during these maximal effort isometric exertions (Johnson & Woldstad, 1993).

4.4 Discussion

4.4.1 Handwheel Tangential Forces and Torque During 'Cracking'

According to several studies (Wood *et al.*, 1999/2000; Schulze *et al.*, 1997a & 1997b), the physiological capabilities of the operator to impart tangential force, thus producing torque about the handwheel seems to be significantly less than the amount of torque required to actuate handwheels found *in situ* (Parks & Schulze, 1998; Jackson *et al.*, 1992). Torque wrenches and not handwheels were used by both Parks and Schulze (1998) and Jackson *et al.* (1992) to determine the actual torque values required to actuate the handwheels, regardless of handwheel diameter. Studies that did use handwheels, in laboratory settings, determined that torque production is directly proportional to handwheel diameter, as would be expected by definition, and that large tangential forces can indeed be developed by operators. When a gradual, ramp to maximum isometric force is exerted, under optimal footing and bracing conditions while using a conventional rim grip, Woldstad and McMulkin (1995) determined that 90 Nm (322 N) and 150 Nm (541 N) torques could be exerted on a 56 cm diameter vertically oriented rail brake

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handwheel by females and males respectively. When a spoke grip was used, these values increased to 97 Nm (347 N) and 171 Nm (614 N) respectively. Thus, it seems that under certain conditions, human operators are capable of producing torques in the lower range of what would conceivably permit the actuation of some industrial handwheels found *in situ*. Whether this can be accomplished safely and repeatedly over a shift must be considered and investigated. More research is needed in order to clarify and define operator capabilities for handwheels oriented in various heights, pitch angles, distances from operators, environments as well as actuation frequencies, which all combine to form a complex human-machine interface in which all facets must be optimized in terms of human performance. This must be accomplished before comprehensive industrial handwheel actuation guidelines can be put forth. These contributing factors will be discussed further in sections 4.4.2 through 4.4.6. In addition to these issues, no study found in the literature examined the electromyographic (EMG) activity of the muscles responsible for producing these forces; the authors view this as a substantial gap in the knowledge concerning this task. Furthermore, no postural analysis, kinematic description of the task nor psychophysical assessment of the perceived exertions involved in the task, either in a laboratory simulation or in the field was found, again this is viewed as a substantial gap that should be addressed in future research.

4.4.2 Handwheel Tangential Forces and Torque During Continuous Actuation

Unfortunately, a paucity of information concerning continuous industrial handwheel actuation was found in the literature. As noted earlier, this task may be more physically demanding than the task of producing the initial isometric torques required to begin ('crack') the handwheel turning task (Jackson *et al.*, 1992). Although continuous hand cranking has been studied in the past in a limited sample with some useful results, this task is distinctly different in terms of movement patterns from handwheel actuation (Raouf *et al.*, 1986 & 1984). More research is needed to define the physiologic loads in terms of endurance strengths, oxygen consumption and heart rate for continuous industrial handwheel actuation.

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4.4.3 Handwheel Diameter

The relationship between industrial handwheel diameter and operator torque production capability is more clearly defined than the issue of isometric strength and endurance. Handwheel diameter is equal to twice the handwheel radius, and radius is a term in the torque equation (torque about the center of the handwheel [Nm] = tangential force (N) X radius [m]). Thus, it is recommended that large, spoked, handwheels be used whenever possible to decrease the tangential force requirements and make as much use as possible of the larger lever arms (radii) associated with larger diameter handwheels. These handwheels must not be so large that effective upper extremity posture is affected; hence a careful balance must be achieved between operator comfort and spatial requirements. More research is needed to determine optimum wheel diameters in terms of operator comfort and torque production capability.

4.4.4 Handwheel Rim Shape

The effect of rim shape in both large and small handwheels has been examined (Shih *et al.*, 1997; Shih & Wang, 1997; McMulkin & Woldstad, 1995) and in all instances, rim shape has been determined to affect grip strength and hence the overall capability of the human operator to exert a tangential force and resulting torque. Increasing the coefficient of friction between the hand or glove-hand component and the handwheel through knurling (Shih *et al.*, 1997) or zig-zag shaped rims (McMulkin & Woldstad, 1995), as well as using larger diameter rims which increases the contact area significantly increases the torque production capability of operators over currently employed smooth or slightly grooved rim designs. Also, utilizing the spokes to actuate the handwheel increases the torque production capability, presumably due to poor coupling factors at the rim of the handwheel. Operators could exert greater torques in spite of a decreased lever arm in this case. Thus, if currently employed smooth edge designs were replaced with more efficient edge designs, operators could take advantage of both an increased coefficient of friction, larger diameter rim edge, and the longer lever arm associated with actuating handwheels while utilizing the rim, the furthest point from the center of the handwheel.

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4.4.5 Handwheel Orientation Relative to the Operator

Handwheel orientation relative to the operator encompasses issues such as the height (above grade), pitch angle and the distance from operator to the handwheel. These issues have all been addressed in the literature, however none to any degree of satisfaction due to the small spatial envelopes tested and the low number of participating subjects (Wood *et al.*, 1999/2000; Schulze *et al.*, 1997a). More research is needed to quantify handwheel actuation proficiency at below knee and above shoulder levels. Ideally, all industrial handwheels should be located within the comfort zone of the operator, based upon established anthropometric values. However, in practice, many existing facilities utilizing handwheels have a substantive portion of their handwheels located in awkward positions. The pitch angle of the handwheel is another issue related to orientation that may affect the operator's ability to exert torque. Industrial handwheel pitch angles of 0°, 45° and 90° (relative to the horizontal) are frequently observed in the field. Differing body kinematics are required to actuate handwheels operating in different planes. For example, vertically oriented handwheels (90°) located at or above the shoulder height may be actuated with the aid of the body mass vector while horizontally oriented handwheel actuation may only benefit from a varying portion of this body mass vector depending on the distance of operation. Incorporating EMG analysis into the task examination would permit a more detailed examination of this factor. Finally, the distance the operator is from the handwheel will also contribute to the torque production capability. This factor is linked directly to section 4.4.6. Often, operators cannot assume an optimum posture due to various obstructions located near the handwheel.

4.4.6 Handwheel Environment

The presence of obstructions that limit the freedom of movement the operator has in the workspace surrounding the handwheel to be actuated will affect the ability to produce optimum torque. Only one study has addressed the issue of distance between the operator and the handwheel (Wood *et al.*, 1999/2000). The two distances examined were only separated by 15 cm and hence do not necessarily represent what would be expected in severely limited workspaces, as are frequently observed in the field. The relationship

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between unrestricted workspace and restricted workspace in terms of freedom of movement for the task of industrial handwheel actuation should be examined in further detail. It would be expected that restricted space limits the torque production capability of the operator, however the degree to which it affects capacity must be established. The lack of optimal and stable footing or bracing is another issue that is detrimental to optimal handwheel actuation. Many handwheels must be actuated while standing or sitting upon a large pipe, the degree to which factors such as this, and others, affect the operator's ability to complete the task must be investigated.

4.5 Conclusions

Based upon the review of literature concerning industrial handwheel actuation contained herein, it is evident that a significant portion of handwheel control devices are designed without any attempts to address the anthropometrics of the operator, nor the biomechanical or physiological work capacity of the operator. Only through comprehensive examination of the variables affecting the operators ability to perform the task outlined in this article can meaningful, ergonomically based guidelines for industrial handwheel actuation be put forth. Some of the most pressing questions urgently requiring answers are listed below:

1. What effect do handwheel height (above shoulder and below knee), pitch angle, distance from operator, degree of foot support and freedom of movement within the workspace have on the operator's ability to exert a maximal isometric effort to "crack" a valve handwheel?
2. How does the neuromuscular activity of the principal muscles involved in handwheel actuation change in relation to the variables listed in question 1?
3. What level of physiological demand is placed upon the aerobic capacity (oxygen consumption), heart rate and the endurance strength required for safe completion of the handwheel actuation task in relation to the variables listed in question 1?

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4. What body posture and kinematics are employed by operators during the actuation of handwheels in relation to the variables listed in question 1?
5. What effect do psychophysical variables such as perceived physical exertion have upon the operator's ability to actuate handwheels in relation to the variables listed in question 1?
6. How does repeated industrial handwheel actuation affect the occupational health status of the operator?

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Table 4.1: Recommended design values for industrial handwheel torque and size based upon a vertical handwheel orientation. Adapted from Murrel (1965) as cited by Woodson *et al.* (1992).

Torque (Nm)	**Wheel Diameter (cm) 96 to 121 cm above grade**	**Wheel Diameter (cm) 96 below or 121 cm above grade**
2.2 – 4.4[1]	15[2]	25
4.4 – 6.6	25	40
6.6 – 9.9	25	40
> 9.9	40	40

1 Units converted and rounded up from inch-pounds of torque to Newton meters; 1 in-lb = 0.11 Nm
2 Units converted and rounded up from inches to centimeters; 1 in = 2.54 cm

Table 4.2: Recommended design values for industrial handwheel tangential force based upon frequency of actuation. Adapted from the State Committee for Standards of the USSR (1984), as cited by Schulze *et al.* (1997a).

Activity Description	**Frequency of Use per Shift**	
	< 5	**5 - 16**
Primarily by fingers	-	-
By hand with forearm	59[1] N	29 N
Entire arm	147 N	39 N
Two arms	196 N	59 N

1 Units converted and rounded up from kilograms of force to Newtons; 1 kgf = 9.81 N

Table 4.3: Recommended design values for industrial handwheel size, rim size and tangential force. Adapted from the Eastman Kodak Company (1983).

Parameter	**Recommended Design Value**
Handwheel Diameter	18-53 cm
Rim Diameter	20-50 mm
Resistance at Rim (tangential force)	
One-handed operation	20-130 N
Two-handed operation	20-220 N

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Table 4.4: Summary of studies directly related to industrial handwheel actuation and the human operator. Diam., height and angle refer to handwheel diameter, height above grade, and angle refers to pitch angle, 0° is horizontal. M = Male; F = Female.

Study	n	Task	Diam. (cm)	Height (cm)	Angle (deg)	Summary and Conclusions
1	144 M 126 F	Isometric strength and endurance using a handwheel	Torque wrench	High Low	0 90	Isometric valve cracking strength was assessed in 8 positions for the total sample while endurance was assessed in 26 males and 25 females. No specific strength data are provided. The authors concluded that both isometric valve cracking and valve turning endurance were related to standard isometric strength scores. The strength demands of the endurance task exceeded those of the cracking task, some workers may have the physical strength to crack the valves, but lack the aerobic capacity and endurance strength to fully open or close them. Strength tests were determined to be valid for defining the physiological capacity to crack, open and close industrial valves in the field.
2	12 M	Isokinetic strength using handwheels	40.6 22.9 20.3 17.8	81.0 102.0 122.0	0 90	Main effects of wheel size and height were statistically significant. Post hoc tests revealed that the large wheel produced the largest forces over medium, small, and small handled. The medium wheel produced larger forces than the two smaller wheels and less than the large wheel. There was no difference between the smaller wheels, heights or angles.
3	12 M 12 F	Isokinetic strength using a handwheel	43.82	50.8 76.2 102.0 127.0 152.0	90	Operator distances of 37.0 and 52.6 cm were also tested. Main effects were found for gender, height and distance, as well as the interaction between gender and distance. Females produced 47% of the torque males did. Post hoc tests revealed no differences between heights, or distances. Correlations were noted between anthropometric data and torque.
4	336 valve hand-wheels	Cracking force using a modified torque wrench on handwheels in the field	20.32 25.40 30.48 35.56 40.64	50.0 76.00 101.0 127.0 152.0 177.8 203.0 228.0 250.0	0 90	Also studied in-line pressure. Handwheel diameter, height and in-line pressure were significant. Larger handwheels required more force to crack than smaller wheels. More force was required to open a closed valve than to close an open valve. More torque was required to operate valves with heights of 228 cm above and 50 cm below the grade than at all other heights.
5	125 M 125 F	Isometric strength using a handwheel	56.0	76.2	90	Studied various grips. Range of tangential wheel forces was 393N to 614N in males and 235N to 348N in females. Female strengths were 42% lower than male strengths, 3s average measurements were 26% lower than ramp to maximum and rim grip was 12% lower than with spoke grip. Whole body strength tests, grip and gender predicted tangential wheel forces very accurately.
6	12 M 12 F	Isometric strength using a handwheel	56.0	76.2	90	Four different wheel shapes were tested: standard, cylindrical, spheres, zigzag. Wheel shape significantly affects tangential wheel force production. Zigzag shape produced force values 54% greater than the standard wheel, sphere shape was 16% higher while cylindrical was 5% higher. Grip is very important for this task. Again, ramp to maximum torques were higher than 3s average.
7	8 M 8 F	Isometric strength using a handwheel	56.0	76.2	90	An optimization-based biomechanical model of the handwheel turning task was developed. The compressive force acting on L3/L4 was estimated to be 1644N for females and 6926N for males.

Study 1: Jackson *et al.* (1992); Study 2: Schulze *et al.* (1997a); Study 3: Wood *et al.* (1999/2000); Study 4: Parks & Schulze (1998); Study 5: Woldstad *et al.* (1995), includes Woldstad *et al.* (1992); Study 6: McMulkin *et al.* (1995), includes McMulkin *et al.* (1993); Study 7: Johnson & Woldstad (1993)

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Table 4.5: Summary of studies indirectly related to industrial handwheel actuation and the human operator. Diam., height and angle refer to handwheel diameter, height above grade, and angle refers to pitch angle, 0° is horizontal. M = Male; F = Female.

Study	n	Task	Diam. (cm)	Height (cm)	Angle (deg)	Summary and Conclusions
8	20 M 20 F	Isometric strength using a small handwheel	8.4 8.0 9.3 9.1 9.2 9.3	Shoulder height	0 90	Subjects turned six small valve handwheels [various diameters and edge types] using two grips [power and precision] in two directions [clockwise and counter clockwise] and three planes (frontal [90], sagittal [90], transverse [0]). Significant main effects were found for all variables. Power grasp produced greater torque than precision. Greater torque could be produced in the transverse plane versus sagittal and frontal.
9	20 M 20 M	Isometric strength using a small handwheel	5.5 5.5 6.2 6.2 6.9 7.5 9.8 9.5 12 12	Elbow, shoulder and overhead heights	0	Subjects turned a small valve handwheels of various diameters and edge types using four different glove conditions (1 layer cotton, 2 layer cotton, rubber, no gloves), three heights and two directions (clockwise and counter clockwise). All main effects were significant. Gloved trials produced greater torques than not gloved and shoulder height produced the highest torques.
10	5 M	Isometric strength using a hand crank	-	40.6 60.9 81.3	0 30 60	Crank direction (clockwise and counter-clockwise) was also studied. Main effects for direction, height and angle were significant, as well as the interaction between pitch angle and direction. More force was exerted under the counter-clockwise direction. More force was exerted at the lower heights than the higher height. 0 deg pitch angle produced more force than 30, and 30 more than 60. No post hoc tests are reported.
11	5 M 5 F	Continuous and intermittent cranking	10.21[1] 20.3 30.5	-	0 45 90	Pitch angle of crank, direction [clockwise and counter clockwise], crank radius and resistance to be overcome (2, 4 and 6 Nm) for continuous and intermittent cranking was examined. All factors significantly affected cranking performance. As crank radius, resistance, and angle increased, cranking rate decreased. Cranking rate reached a maximum in the frontal plane.
12	5 M	Continuous cranking	10.21[1] 20.3 30.5	-	0 45 90	Pitch angle of crank, direction (clockwise and counter clockwise), crank radius and resistance to be overcome (2.2 and 6.6 Nm) for continuous cranking were examined. All factors significantly affected cranking performance. As crank size, resistance, and angle increased, cranking rate decreased. Cranking in the clockwise direction was superior to the counter clockwise direction.
13	259 M 10 F	Isometric strength using a truck steering wheel	55.9	-	60	Subjects were instructed to gradually exert a maximal isometric force over 2-3s and asked to hold for 15s in a clockwise direction in three hand positions (preferred position; 3 and 9 o'clock, and 1 and 7 o'clock). There was no difference in the peak force between the 3:9 and preferred hand positions, however 1:7 produced substantially less torque.
14	40 M 40 F	Isodynamic wheel turning	40.64	Waist height	90	Torso kinematics was examined during isodynamic wheel turning at 40% MVC (maximum voluntary contraction) in 40 healthy controls and 40 low back pain patients. Control subjects produced significantly higher levels of isometric torque and completed significantly more wheel-turning repetitions than patients. Patients exhibited significantly less upper torso and pelvic motion, upper torso rotation and lateral trunk flexion than controls.

Study 8: Shih *et al.* (1997); Study 9: Shih & Wang, (1997); Study 10: Schulze *et al.* (1997b); Study 11: Raouf *et al.*, (1986); Study 12: Raouf *et al.*, (1984); Study 13: Sanders (1981); Study 14: Rudy *et al.*, (1995)

[1] Refers to crank radius and not handwheel diameter.

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Figure 4.1: Two workers at a petroleum refinery employ a wrench to actuate an industrial valve handwheel.

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Chapter 5

A Preliminary Electromyographic and Psychophysical Study of Industrial Handwheel Operation in the Field[1]

[1] This chapter has been submitted for publication in *Human Factors and Ergonomics in Manufacturing*. It is currently in the peer review process. AMELL, T.K., KUMAR, S. & NARAYAN, Y. A Preliminary Electromyographic and Psychophysical Study of Industrial Handwheel Operation in the Field.

5.1 Introduction

Large handwheel-based control devices are used extensively in numerous industries to control processes (Amell and Kumar, 2001). Their operation has been reported to be the most physically demanding task that process operators are required to perform (Jackson *et al.*, 1992). Physically demanding tasks are associated with the development of occupational musculoskeletal injuries and illnesses (Kumar 2001, Keyserling 2000a and b) and hence thorough understanding of the nature of these tasks will significantly aid in injury and illness control and prevention efforts.

The task of industrial handwheel operation can be divided into two general phases. Actuation, commonly referred to as 'cracking' or 'breaking' occurs when the handwheel is rotated from a locked to an unlocked position. Operation or 'full actuation' refers to the phase of the task when the handwheel is rotating about its axis towards an open or closed position. Typically large static forces must be exerted by the operator upon the handwheel during actuation, and lesser forces must be exerted during operation. Operation may require up to 15 minutes of continuous rotation in some circumstances, such as emergencies when entire operating sectors of a process facility must be shut down to avert or abate an incident or disaster (Jackson *et al.*, 1992). This issue is compounded due to various design variables such as pitch angle orientation, and height above the grade in addition to the strength and aerobic demands of the task. Although lesser forces may be required to operate the handwheel to its limits, it has been reported that this phase of the task may place more strain upon to the operator than the initial high levels of exertion associated with actuation (Meyer *et al.*, 2000, Jackson *et al.*, 1992).

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The majority of published reports involving industrial handwheel operation have focused on the static actuation forces and torques and not the dynamic component of this task (Amell and Kumar, 2001). As a result, only a few studies investigating continuous handwheel operation have been reported in the literature (Meyer *et al.*, 2000, Wood *et al.*, 1999/2000, Schulze *et al.*, 1997, Raouf *et al.*, 1986). Of these, several different study designs have been reported, including those utilizing isokinetics and hand cranks. Studies using isokinetic dynamometers are of limited applicability due to the fact that handwheel operation rarely involves proportional resistance. Hand cranks alter the mechanics of the movement and hence are not directly applicable either, although both of these types of studies do offer some guidance in the design of handwheel-based control devices. Only two studies found in the literature are applicable to continuous handwheel operation (Meyer *et al.*, 2000, Jackson *et al.*, 1992).

Meyer *et al* (2000) concluded that continuous handwheel actuation for 2 minutes induces high cardiorespiratory and psychophysical strains on the operator in a laboratory setting. Two horizontal pitch angle orientations at different heights and one vertical orientation were examined with respect to two levels of torque demand, 35 and 20 Nm. Work output and heart rate were not affected by handwheel pitch angle orientation. Oxygen consumption was significantly lower when the handwheel was vertically oriented. In addition, work efficiency was greatest in the vertical position. The high torque demand induced greater perceived exertion than the low torque demand and no difference was reported between handwheel positions.

Jackson *et al.* (1992) reported that an operational torque of over 400 Nm was required to 'crack' 93% of the valve handwheels at a process plant while a power output of 32.2 W was sufficient to open or close 75% of the emergency shut down valves in 15 minutes or less. Tests of operator capabilities revealed that only 19 of 51 workers (37%) completed the 15 minute protocol at this power output, and of the 32 (63%) who could not complete the test, 20 halted the task after less than 4 minutes (Jackson *et al.*, 1992).

All studies reported in the literature involved some form of laboratory-based simulation. Those that did incorporate field-based data used torque wrenches to obtain handwheel actuation forces. No studies reported in the literature have described the muscular activity during this task, nor has the perceived exertion been reported upon for

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existing handwheel designs in the field. This observation was viewed as a gap in the understanding of the physical and psychophysical demands on operators during industrial handwheel operation and served as the logic for carrying out the present study.

5.1.1 Purpose

The purpose of this study was to determine the impact of different types of valve handwheels, pitch angle orientations and phases of task upon the muscular activity, torque requirement and psychophysical perception of industrial handwheel operation in a field setting.

5.2 Methods

5.2.1 Participants

A convenience sample of five healthy male workers who reported no musculoskeletal injuries at the time of the experiment participated in the study. Prior to studying this sample, two workers acted as a pilot sample to help establish the final study protocol. All workers were process operators employed at a large petroleum refinery. The study was approved by the University Health Research Ethics Board, and the management team at the refinery. The workers were recruited at random from the population of process operators assigned to a shift team. All participants provided informed consent. In addition, the workers also completed the PAR-Q questionnaire to assess their fitness for physical work (Shephard 1988). The mean age, weight and height of the participants was 38 ± 9.3 years, 98.6 ± 10.7 kg, and 181.6 ± 4.5 cm. All of the workers were right hand dominant. The mean number of years on the job was 3.5 ± 3.0, and the range was 0.3 to 9 years.

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5.2.2 Participant Preparation

Eight surface EMG electrodes were placed over the respective muscle bellies of the erector spinae at the L4 lumbar level, the flexor carpi radialis, biceps brachii, and the anterior deltoid bilaterally. A ground electrode was placed above the right acromion. Prior to attaching the EMG electrodes, the skin was thoroughly cleansed with rubbing alcohol and the hair removed by shaving when necessary. The electrode leads were input into the amplifier pack worn on the worker's belt. The workers all wore fire retardant coveralls and necessary personal protective equipment (PPE).

5.2.3 Experimental Design

The workers were required to actuate four handwheels of various sizes, pitch angles and heights above the grade in an operational petroleum refinery. After the participants were prepared for the experiment, standard strength tests were employed in order to normalize the EMG activity. Then the participants and the principal investigator proceeded to each location and actuated the handwheels in a random order. The handwheels were actuated normally, as they would regularly during the course of their shift, as well as when using a modified torque wrench. Upon completion of the task at each handwheel, three psychophysical tests were administered.

5.2.3.1 EMG Normalization

The normalization of the EMG signal was accomplished through the use of three maximal effort isometric strength tests. The first of these tests was of bilateral power grip for the flexor carpis radialis (FLX) using a Jamar hand grip dynamometer (Asirnow Engineering, Los Angeles CA, USA). All participants were seated with the shoulder in the neutral position, and the forearm flexed to 90° while resting comfortably on the arm of a chair. Participants were instructed to gradually increase their effort over 2 seconds, after which they were to be exerting their maximum force. They were to hold this maximal effort for 3 additional seconds. The second test was of arm strength for the biceps brachii

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(BCP) whereby the participants stood on a platform and pulled vertically on a handle attached to a firmly fixed steel chain using both hands. The participants were instructed to limit the force generation to the arms. The shoulder was in the neutral position, and the forearm angle was 90^{o}. In the path of the chain was a load cell (Omega Type S load cell, model LCCB-1K, Omega Engineering, Stamford, CT, USA). The third test was of maximum effort stoop lift strength for the erector spinae (L4) whereby the participants pulled vertically on the aforementioned handle attached to the chain and platform using both hands. Since no strength test data could be acquired for the normalization of the bilateral anterior deltoid muscle activity (DT), these data were normalized against the field study condition inducing the greatest amount of EMG activity, which was the 'cracking' phase of activity on handwheel V1, without the wrench. The same instructions concerning the length of the trials and gradual increase of force used in the grip strength tests were applicable to the arm and stoop strength tests. All strength based EMG normalization tests were replicated 3 times and the mean of these trials was used in all subsequent analyses.

5.2.3.2 Handwheels

The characteristics of the handwheels studied are listed in table 1. Handwheels were selected for inclusion in the study based upon the frequency of operation, and the need to test several different types, orientations, and sizes. Unfortunately, the most difficult handwheels to actuate, as well as those known to have contributed to injuries, were not permitted to be examined in the study. As a result, the handwheels included in the analysis were deemed of 'moderate' difficulty to operate by the process operators, but were however operated more frequently (on a daily basis) than the other more problematic handwheels.

5.2.3.3 Handwheel Operation Task

Upon arrival at each handwheel, and after the usual pre-task procedures, which consisted of proper identification and clearance for actuation from the process control

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center, the participant was asked to operate the handwheel as they normally would under everyday working conditions. The experimental conditions are listed in table 2. Additionally, the workers were asked to operate the handwheel while using a modified torque wrench and a handwheel coupling device. Whenever workers cannot exert sufficient force to actuate or 'crack' the handwheel using their hands, they frequently turn to the use of wrenches or 'cheater bars.' This aspect of the study is described by condition codes VXW1 through VXW4 as outlined in table 2. 'Cracking,' as noted above, refers to the initial opening of the valve using the handwheel, and is performed by applying a counter-clockwise force while 'Seal' or 'sealing' is the act of forcefully closing the valve (clockwise). 'Normal open' is the part of the task when the handwheel is rotating freely, dependant upon lubrication, in the counter-clockwise direction towards being fully open. 'Normal close' is the part of the task when the handwheel is rotating freely, again dependant upon lubrication, in the clockwise direction towards closing. During each condition, the electrical activity of the eight muscles as well as the force (where applicable) was recorded in real time via a portable notebook computer. Each trial was 5 seconds in duration.

Since this field study took place in a fully operational and on-line petroleum refinery, while workers were performing normal daily tasks, there is an inherently high level of validity associated with these data. However such a high degree of validity is not without disadvantage as some conditions could not be replicated after the initial two participants (and two additional pilot participants) completed the protocol. This was due to fully actuating a handwheel 'artificially' when it was not scheduled for full actuation, as a result, process was affected and we were unable to actuate two of the handwheels on the third, fourth and fifth sessions. Thus, only the first two workers actuated valve handwheels V2 and V3, while the remaining three workers were limited to actuating valve handwheels V1 and V4, hence complete sets were only available for V1 and V4 for all five workers in the sample.

Upon the completion of all phases of the task associated with each handwheel, the workers completed three psychophysical questionnaires. Additional information concerning subjective feedback was solicited in the form of an unstructured interview.

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5.2.4 Equipment

5.2.4.1 Electromyographic Setup

The bipolar EMG electrodes were of the differential knife edge type (model MDI-X10; Neuromuscular Research Center, University of Boston, MA, USA) and measured 1 cm x 1 mm with a 1 cm inter-electrode distance. The electrodes had an on-site gain of 10 and a high pass filter of 6 Hz. The system gain was 1000 to 3000 depending on the channel and the bandwidth was 20 to 500 Hz. The EMG signals were pre-amplified and input to an isolated amplifier system. The pre-amplifier and amplifier were calibrated within a range of 100 μV to 5 mV. Each EMG channel was calibrated prior to the experiment by feeding a known signal. The output of EMG signals from the amplifier system was input into the interface box and power supply, and then ultimately input into the AD converter on a notebook computer.

5.2.4.2 Modified Torque Wrench and Handwheel Coupling Device

Real-time force measurement was made possible though the use a modified torque wrench. Two strain gauges (model SG-6/120-LY11; Omega Engineering, Stamford, CT, USA) were securely fixed in the directions of movement (clockwise and counter-clockwise) to a standard 40" (101 cm) torque wrench. Output from the torque wrench was input into a signal conditioner, then input into the interface box, from which all data were input into the AD converter of the notebook computer. The torque wrench was equipped with a 1" (2.5 cm) drive which was inserted into a custom built handwheel coupling device capable of being fixed to handwheels V1, V2 and V3. This coupling device was only used on the horizontally oriented handwheels. The handwheel coupling device was constructed of steel and securely fixed to the hub of the handwheel, thus circumventing the need of the handwheel, as a result, all force exerted on the torque wrench was transferred directly to the hub. For all recorded measurements involving the modified torque wrench, and the handwheel coupling device, the workers held the wrench in such a manner that the center of their grip was at a known distance (92 cm) from the wrench's

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axis of rotation. All torque calculations were derived based upon this lever arm distance (0.92 m).

5.2.4.3 *Data Acquisition*

All data were collected on a portable notebook computer through a PCMCIA AD acquisition board (model DAQ 700; National Instruments, Austin, TX, USA). Sampling rate was set to 1000 Hz.

5.2.4.4 *Psychophysical Questionnaires*

A small group of validated and quickly administered tests formed the battery of psychophysical questionnaires. The questionnaires used were the Borg Rating of Perceived Exertion Scale (RPE), the Visual Analog Scale (VAS), and the Body Part Discomfort Rating (BPDR). Please refer to Kumar *et al.* (1999) for more information on these measures. The RPE is an interval scale ranging from 6 to 20 whereby the respondent circles a number corresponding to their level of perceived exertion, based upon the descriptors. The VAS consists of a 10 cm horizontal line with the descriptors 'most comfortable' and 'most uncomfortable' at the ends of the line whereby the respondents mark their level of comfort along the continuum. The BPDR consists of a graphical depiction of a human figure divided into 'left' and 'right' body parts whereby the respondents indicate their level of perceived discomfort on a scale ranging from 1 to 10 (Corlett and Bishop, 1976).

5.2.5 Analysis

Customized data management and editing software was used in the processing of the EMG. Normalization of the maximum EMG signal was accomplished using SPSS (version 10.0.5). Raw EMG signals were converted to Root Mean Square (RMS) EMG signal using a time constant of 25 ms. These normalized values, in percent, were used in all subsequent comparisons. These values were subject to repeated measures Analysis of

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Variance (ANOVA). Torque values were analyzed in a similar fashion. Maximum forces were acquired in pounds and converted to Newtons of force, then multiplied by the lever arm distance to obtain the torque measurement and subjected to ANOVA. The psychophysical scores from to the RPE, and VAS were subject to ANOVA. Body Part Discomfort Ratings are described in frequency of response format. All statistical tests were carried out using SPSS and were measured against the α level of 0.05.

5.3 Results

5.3.1 Electromyography

Figure 1 depicts an example of the EMG and force data collected over a 5 second trial. This example is representative of all data collected in the study. Figure 2 A depicts the normalized EMG activity with respect to each handwheel tested. Handwheel V2 induced the most muscle activity while handwheel V3 induced the least. Overall, handwheel V2 induced 41%, 98% and 141% more normalized EMG activity than V4, V1 and V3 respectively. The normalized activity of RFLX was greatest while actuating handwheel V2, followed by V4 and V1. The greatest activity of the LDT was induced by actuating V4, followed closely by V2 and V3. Handwheels V2 and V4 induced the greatest activity in RL4 while only V2 induced high activity in LL4.

The main effects for muscle, handwheel type and phase of task significantly affected the normalized electromyographic activity ($p < 0.05$). No interaction effects were found to be statistically significant. In general, the right flexor carpi radialis (RFLX), left anterior deltoid (LDT) and both the right and left erector spinae at the L4 level (RL4 and LL4) were active muscles. The left flexor carpi radialis (LFLX) and the right and left biceps brachii (RBC and LBC) displayed the least activity. Only the muscle activity of the RFLX was significantly greater than all other muscles with the exception of LDT and RL4.

Figure 2 B. depicts the normalized EMG activity with respect to the phase of the task. Normal opening induced more EMG activity than normal closing, cracking or

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sealing. The RFLX, LDT, RL4 and LL4 all exhibited high levels of normalized EMG activity during normal opening of the valve.

5.3.2 Force

Figure 3 depicts the mean maximum torque produced for each handwheel tested as well as phase of task. Neither handwheel type nor phase of task of handwheel task operation significantly affected the amount of torque produced during operation. Larger torques (over 100 Nm) were produced during the sealing of handwheel V1; however the typical torques observed were between 20 and 40 Nm.

5.3.3 Psychophysical Measures

Figure 4 depicts the Borg Rating of Perceived Exertion (RPE) and Visual Analog Scale (VAS). The RPE and VAS were significantly affected by handwheel type ($p < 0.05$). The handwheel perceived to induce the greatest exertion was handwheel V2. Handwheel V4 was perceived to induce the least exertion, while handwheels V1 and V3 were similar in the perceived exertion associated with their operation. With respect to the VAS score, handwheel V2 is by far the most uncomfortable to operate. A similar pattern was observed for the VAS for the remaining handwheels as well. The lower back and shoulders were the most frequently reported body parts affected by handwheel actuation, based upon perceived discomfort using the BPDR.

5.4 Discussion and Conclusion

The results indicate that the muscular activity exhibited by the operators varied with the type of handwheel. Handwheel V2 is the control device for a hammer/stop-check valve. This valve requires repeated 'hammering' (back and forth rotary action about the axis) whereby the operator must quickly accelerate the handwheel over a short period of travel before impacting the 'stopper.' As a result, the operator is subject to jarring motion while rotating the handwheel. The air temperature surrounding this handwheel was extremely hot and this task required the operator to stand upon a curved surface while

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reaching to a relatively high height in order to actuate the handwheel. Overall, these factors combined to form a task that required significantly more electromyographic activity than the other handwheels tested.

The high level of activity associated with the right flexor carpis radialis was expected since this muscle is a primary contributor to grip strength. Handwheel actuation forces and movements are highly dependant upon grip strength (McMulkin and Woldstad 1995). In most instances, the operators utilized their right hands to actuate, with the left hand either aiding in this movement or stabilizing their torso in the case of handwheel V2 (which also required forward flexion of the arm via action of the anterior deltoid). The high levels of activity exhibited by the erector spinae at the L4 level indicate that the torso played an active role in this task. It served to maintain posture as well as contribute to the task via left- or right-efforts in support of the upper extremity muscular effort.

The lack of muscular activity exhibited by the biceps brachii during this task may help to explain the results reported by Jackson *et al.* (1992). These authors reported a non-linear relationship between the summed isometric grip, arm lift and torso lift strengths and valve handwheel 'cracking' strength (Jackson *et al.*, 1992). The biceps brachii has been shown not to contribute to a significant degree to the task, perhaps utilizing this test as one of the means to predict handwheel 'cracking' strength is not valid and hence may contribute to injury since pre-employment strength tests of this kind are common in industry (Jackson *et al.*, 1992). The alternative to worker selection through pre-employment strength tests is work system design within the capacities of the operator (ergonomics), perhaps this strategy is more suitable to handwheel design, actuation and operation than such tests based upon the evidence provided herein.

The torque values were modest and are representative of valve handwheel systems of moderate difficulty to operate. The high torque observed during the 'sealing' of handwheel V1 in figure 3 is due to the operators applying large forces on the modified torque wrench to ensure a closed valve. It has been stated elsewhere (Amell and Kumar 2001) that torque values for handwheel operation are not the preferred method of reporting the physical demands as torque is dependant upon the diameter of the handwheel. The net tangential force is the preferred method since this quantity is directly related to the operational torque and to the amount of force exerted by the operator,

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however is not affected by handwheel diameter. Since the modified torque wrench was the only method of acquiring real-time force data while the handwheels were operated in the field, this technique is warranted in this instance. Also, torque wrenches are sometimes used to increase leverage and thereby decrease the force demands on the operator when actuating difficult valve handwheels.

With respect to the level of perceived exertion and comfort, the results are in agreement with the electromyographic activity recorded herein as well as those reported by Meyer *et al.* (2000). Since only two of the workers were permitted to operate handwheels V2 and V3, these data may not reflect to true perceptions of the exertion and comfort associated with this task. However, it was stated by many process operators, including those who participated in this study during the unstructured interview that the 'hammer' type of handwheel is perceived to be more physically demanding than the other handwheels in the sample. Furthermore, the vertically oriented handwheel design was reported by Meyer *et al.* (2000) to induce the least cardiorespiratory and psychophysical load. Since this load is related to the subjectively determined RPE and VAS (Kumar *et al.*, 1999; Garcin *et al.*, 1998; Gamberale, 1985), it is not surprising that the vertically orientated handwheel in this field study was associated with the least levels of psychophysically determined exertion and comfort. This finding may be attributed to the fact that in the vertical handwheel pitch angle orientation, the operator can use the effective force of gravity more efficiently than in horizontal orientation. In addition, the vertical orientation is less likely to be adversely affected by handwheel height above the grade since it can be gripped at any location, whereas in the horizontal orientation, height dramatically affects the operator's ability as evidenced by the high levels of EMG activity and perceived exertion and discomfort associated with handwheel V2.

The observation that the lower back and shoulders were the body regions most frequently reported to be affected by discomfort during this task is not surprising. Furthermore, it coincides with the EMG results. Since the torso may have contributed to stabilization and the handwheel operation effort, thus requiring activity of the erector spine muscle, such discomfort is expected. The shoulder acts to position the upper extremity such that the forearms and hands can interface with the handwheel effectively,

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and although the anterior deltoid did not exhibit high levels of normalized muscular activity, it was active and hence did contribute to the movements.

There are limitations of this field study that should be addressed. Only five workers were tested and two of the handwheels could not be operated by three of the workers during the tests. Under ideal circumstances, more workers would have been included in the sample and more handwheels, or at least all of the handwheels selected for inclusion in the study would have been operated during data collection sessions. However, since this study was carried out in the field and under normal working conditions, it serves as a valid preliminary account of the electromyographic and psychophysical characteristics of industrial handwheel operation.

The levels of normalized electromyographic activity observed are admittedly high. This is indicative of a dynamic activity that either greatly exceeds the statically determined maximal activity or is the result of an ill-matched normalization task to the required movements. The true reason is probably a combination thereof. Since the normalized activity is based upon standardized static postures, it is possible that the activity recorded during the dynamic handwheel operational task was affected by the force-velocity and the length-tension relationship exhibited by skeletal muscle (Kumar and Mital, 1996). All the tasks took place in an environment surrounded by large metal pipes and vessels, as well as high voltage power lines and motors. Every effort was made to restrict their influence through shielding and amplification of the signal, as well as through filtering of 60 Hz noise through the use of a common mode rejection ratio (CMRR). However this may not have been sufficient and the signal could have been negatively influenced by sources unknown to us. Great care was taken when the electrodes were placed upon the skin; however it is possible that their positioning could have resulted in some cross-talk between the muscles during these dynamic movements. This is particularly applicable to the flexor carpis radialis, which is closely flanked by the pronator teres and brachioradialis muscles. Finally, the ambient temperature in the refinery, as well as the area immediately surrounding the handwheels is quite hot and humid, and as a result could have contributed to the proliferation of sweat which may have altered the electrolytic balance of the skin and affected the quality of the electromyographic signal. This could have resulted in shorting of which not all was

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filtered in the analysis; however this is the least likely of contributing factors. In order to reduce the likelihood of this, data collection sessions were scheduled at night during the summer to avoid the increased temperature in the daylight hours. Most operators wore little clothing beneath their fire retardant coveralls.

These factors may have influenced the magnitude of the recorded activity, but not its temporal properties, hence confidence may be placed in the observation that both the flexor carpis radialis and erector spinae muscles contribute significantly to the task of industrial handwheel operation. As a result, these two muscles may be injured by this task when the demand exceeds the capability of the operator. Thus every effort should be made to decrease the physical demands upon the operator through the ergonomic design of industrial handwheel-based control systems.

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Table 5.1: Description of handwheel characteristics. Height of the handwheel is relative to the grade (surface) upon which the worker must stand to actuate the handwheel. Surface contour refers to the shape of the surface, curved refers to standing upon a large pipe while flat generally refers to standing upon a level grate or concrete surface.

Characteristic	Handwheel V1	Handwheel V2	Handwheel V3	Handwheel V4
Radius	18 cm (7 inches)	8 cm (3 inches)	10 cm (4 inches)	25 cm (10 inches)
Diameter	36 cm (14 inches)	15 cm (6 inches)	20 cm (8 inches)	50 cm (20 inches)
Circumference	113 cm (44 inches)	50 cm (19 inches)	63 cm (25 inches)	157 cm (63 inches)
Orientation	Horizontal	Horizontal	Horizontal	Vertical
Height	91 cm	215 cm	104 cm	190 cm
Surface Contour	Curved	Curved	Flat	Flat
Type	Typical rotary valve handwheel, isolation valve	Hammer/stop check valve handwheel	Typical rotary valve handwheel, isolation valve	Typical rotary valve handwheel, isolation valve
Controlling Flow	Recycled H_2O at ambient temperature	H_2O (steam) at 570° C	Slurry at 370° C	Naphtha at 175° C

Table 5.2: Condition descriptions used in the field study of handwheel actuation. 'Crack' or 'cracking,' also referred to as 'breaking,' refers to the initial opening of the valve using the handwheel, and is performed by applying a counter-clockwise force while 'Seal' or 'sealing' is the act of forcefully closing the valve. 'Normal open' is the part of the task when the handwheel is rotating freely (dependant upon lubrication) in the counter-clockwise direction towards being fully open. 'Normal close' is the part of the task when the handwheel is rotating freely (dependant upon lubrication) in the clockwise direction towards closing. CCW = counter-clockwise; CW = clockwise.

Phase of Task	Code	Handwheel V1	Handwheel V2	Handwheel V3	Handwheel V4
Without Torque Wrench					
Crack (unblock); CCW	VXN1	✔	✔		
Normal Open; CCW	VXN2	✔	✔	✔	✔
Normal Close; CW	VXN3	✔	✔	✔	✔
Seal (block); CW	VXN4	✔	✔		
With Torque Wrench					
Crack (unblock); CCW	VXW1	✔	✔		
Normal Open; CCW	VXW2	✔	✔	✔	
Normal Close; CW	VXW3	✔	✔	✔	
Seal (block); CW	VXW4	✔	✔		

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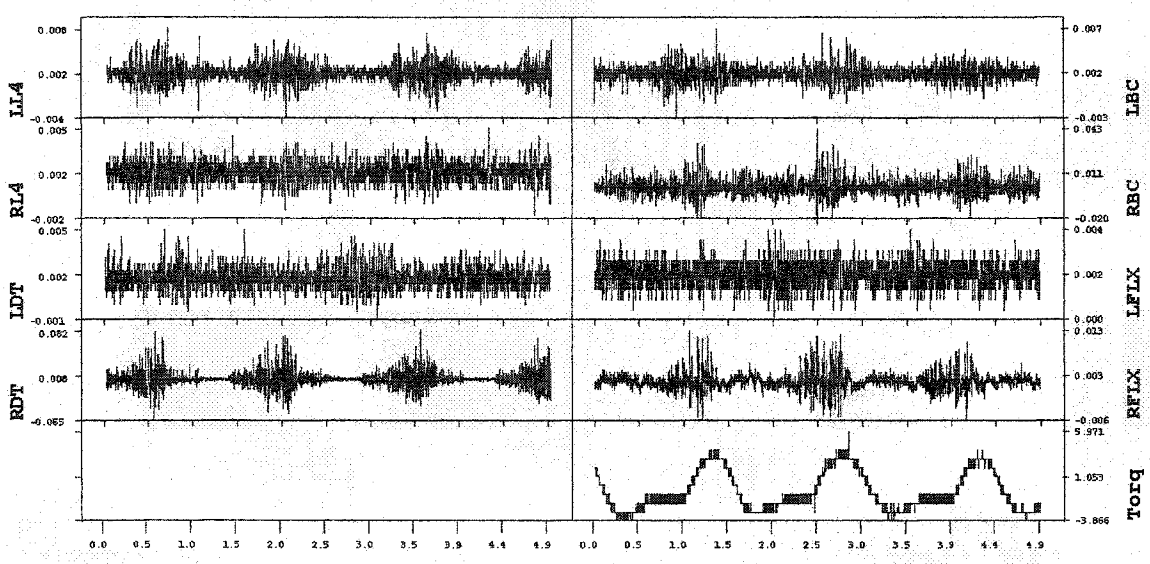

Figure 5.1: Sample EMG data output (mV). LBC = Left Bicep; LDT = Left Deltoid; LFLX = Left Flexor Carpi Radialis; LL4 = Left Erector Spinae at the fourth Lumbar Vertebrae; RBC = Right Bicep; RDT = Right Deltoid; RFLX = Right Flexor Carpi Radialis; RL4 = Right Erector Spinae at the fourth Lumbar Vertebrae. Torq = Torque as measured by the modified torque wrench.

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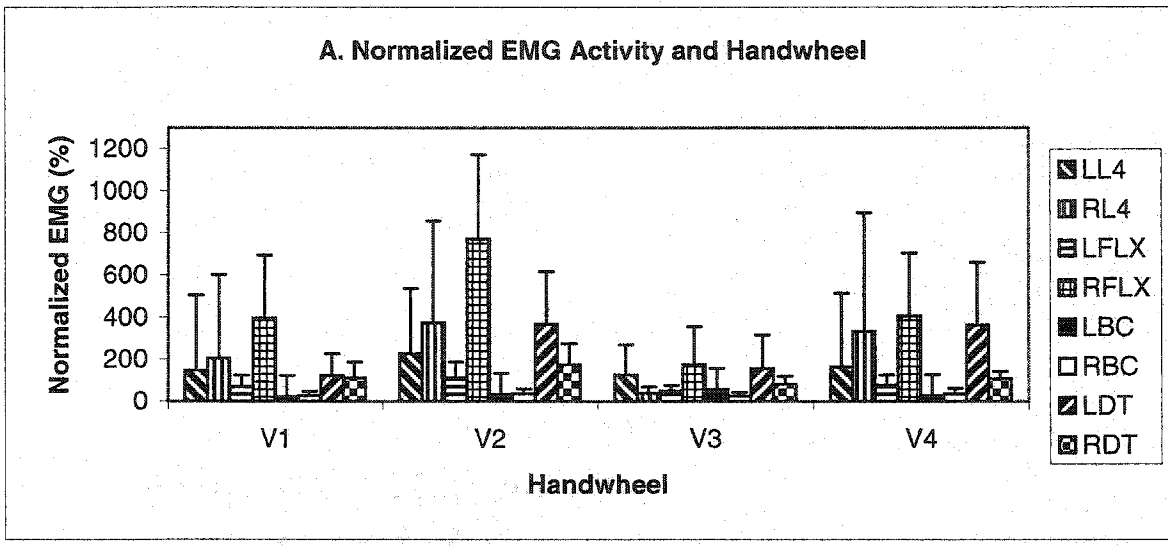

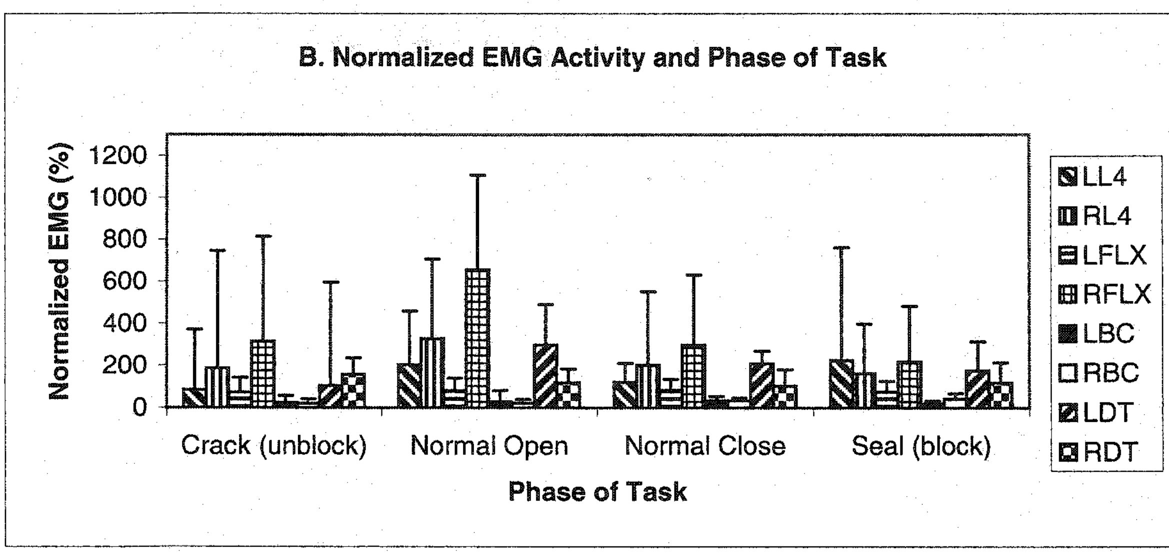

Figure 5.2: A. Normalized EMG activity and type of handwheel for the eight muscles studied. B. Normalized EMG activity and Phase of Task. LBC = Left Bicep; LDT = Left Deltoid; LFLX = Left Flexor Carpi Radialis; LL4 = Left Erector Spinae at the fourth Lumbar Vertebrae; RBC = Right Bicep; RDT = Right Deltoid; RFLX = Right Flexor Carpi Radialis; RL4 = Right Erector Spinae at the fourth Lumbar Vertebrae. Error bars represent the standard deviation.

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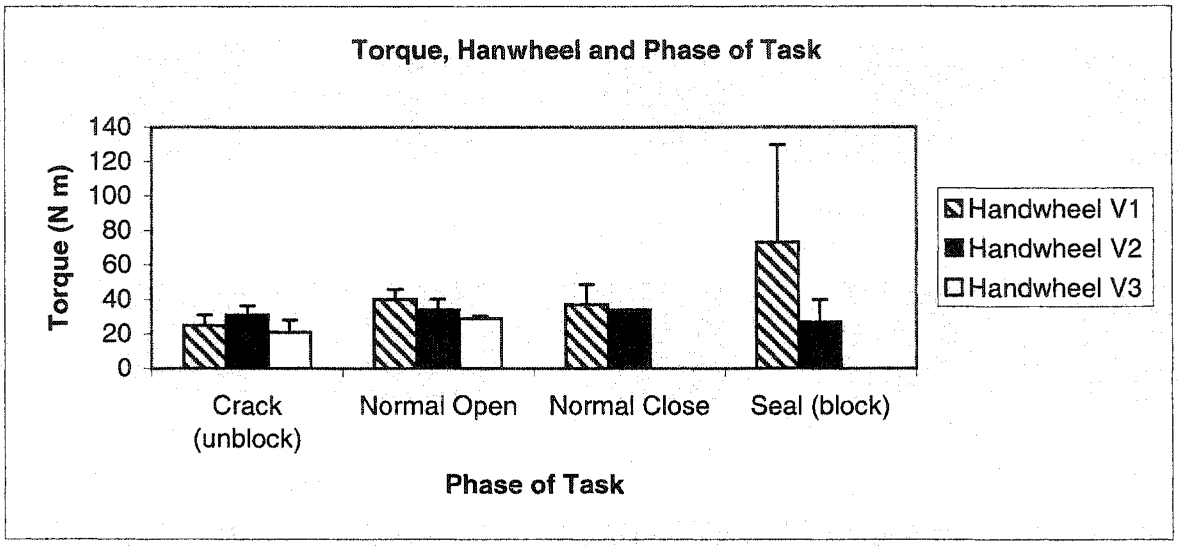

Figure 5.3: Torque values for handwheel and phase of task tested. Error bars represent the standard deviation.

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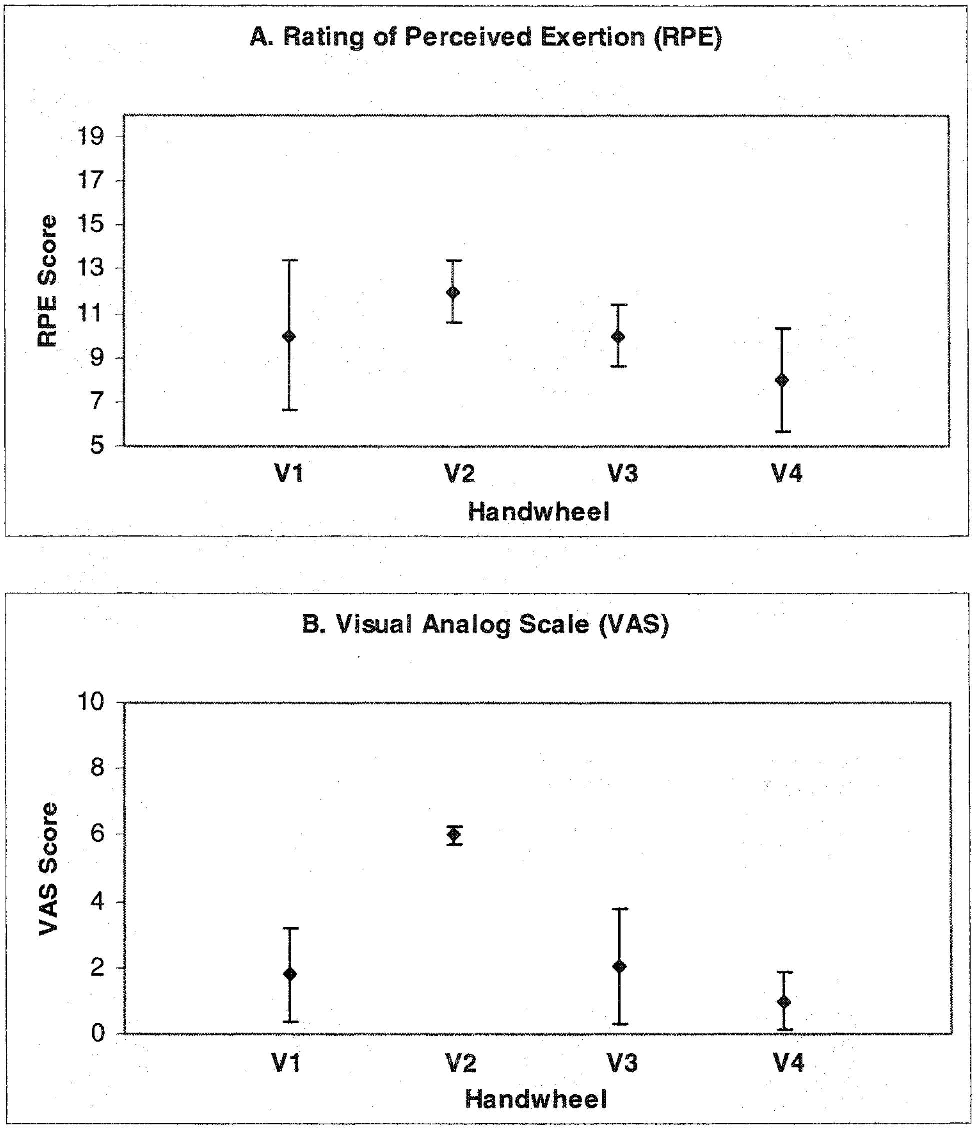

Figure 5.4: Psychophysical ratings of perceived exertion for each handwheel. Figure A depicts the Borg RPE Scale (RPE) while figure B depicts Visual Analog Scale (VAS). Error bars represent the standard deviation.

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Chapter 6

The Effect of Trunk Rotation and Arm Position on Gross Upper Extremity Adduction Strength and Muscular Activity[1]

[1] This chapter has been published in its present format. AMELL, T.K., KUMAR, S., NARAYAN, Y. & GIL COURY, H.C. (2000). The Effect of Trunk Rotation and Arm Position on Gross Upper Extremity Adduction Strength and Muscular Activity. *Ergonomics* 43(4), 512-527.

6.1 Introduction

High levels of muscular exertion are not uncommon during many occupational tasks. Excessive muscular loads have been associated with the development of musculoskeletal injury, particularly in the upper extremity muscles (Hagberg, 1984; Westgaard & Aaras, 1984; Westgaard & Aaras, 1985; Bergenudd, 1988; Ulin *et al.*, 1993; Somerich, 1993; Hagberg *et al.*, 1995; Gil Coury *et al.*, 1997). Static, dynamic (repetitive) upper extremity work, as well as performing the job tasks in awkward positions may also contribute to the development of injury (Bjelle *et al.*, 1981; Westgaard & Aaras, 1984; Järvholm *et al.*, 1991; Kilbom & Persson, 1988; Putz-Anderson, 1988; Kilbom, 1988; Wiker *et al.*, 1989; Chaffin & Andersson, 1991; Hagberg *et al.*, 1995). Awkward upper extremity positions are frequently observed in occupational conditions due to the high level of mobility about the shoulder joint and frequent occurrence of improperly designed job tasks (Westgaard & Aaras, 1984; Westgaard & Aaras, 1985; Aaras *et al.*, 1988; Wiker *et al.*, 1989; Sjogaard *et al.*, 1991). To further compound the issue, axial trunk rotation is typically necessary during materials handling in order to place the upper extremity in a mechanically advantageous position, e.g., rotating the trunk and reaching to lift a box from a shelf. This too has been linked to the development of musculoskeletal injury, specifically low back pain (Garg, 1991).

Industrial tasks frequently require upper extremity adduction exertions during manual materials handling. This is particularly true of materials handling when improper coupling (e.g., handles) or no coupling at all impairs the workers' ability to optimally perform her or his job task. Unfortunately, until recently there has been little strength or

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electromyographic data available pertaining to the adduction pattern of movement about the shoulder joint under occupational conditions (Gil Coury *et al.*, 1998a & 1998b). Flexion as well as adduction of the upper extremity have been noted as commonly occurring awkward positions (Aaras *et al.*, 1988; Chaffin & Andersson, 1991). Excessive upper extremity adduction force has been linked to the development of musculoskeletal disorders in industrial workers in Brazil (Gil Coury *et al.*, 1997).

The adduction force capability of the upper extremity was studied by Gil Coury *et al.* (1998a) and an isometric strength profile was developed. Twelve upper extremity positions and three trunk postures (neutral and 30° left/right rotation) were studied. Significant differences were reported between upper extremity positions, but not for level of axial trunk rotation. In a separate study, Gil Coury *et al.* (1998b) further examined the relationship between upper extremity adduction force and electromyographic (EMG) signal with respect to two additional axial trunk postures (neutral and 60° right rotation) as well as seven arm positions. Significant differences in EMG activity were also reported across upper extremity positions, but not for axial trunk rotation. Gil Coury *et al.* (1998a) reported mean adduction force values that were slightly less in 75% of the axial trunk rotation conditions however no statistically significant differences were noted. Gil Coury *et al.* (1998b) again reported mean and peak adduction force values that were slightly less in the axial trunk rotation postures than the neutral posture, however these differences were not significant.

Since no significant strength differences were reported between neutral and axial trunk postures of 30° left/right nor 60° right rotation (Gil Coury *et al.*, 1998a & 1998b) and Gil Coury *et al.* (1998b) did not report a significant difference between EMG activity with respect to neutral and 60° right axial trunk rotation, it was questioned whether this would also be true of greater trunk rotation (90° left/right rotation). Such trunk postures have been reported in industry (Garg, 1991). The purpose of this experiment was to determine the impact of 90° axial trunk rotation and arm position on upper extremity adduction force and muscle activity. The present experiment was designed to compliment and broaden the findings of previous studies conducted in our laboratory (Gil Coury *et al.*, 1998a & 1998b).

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6.2 Methods

6.2.1 Subjects

Ten male subjects volunteered for the experiment and provided informed consent. The subjects had a mean age of 24 ± 2.6 years, a mean height of 181 ± 5.6 cm, and a mean weight of 73 ± 7.3 kg. Nine of ten subjects were right hand dominant. The subjects reported no musculoskeletal injuries at the time of the experiment.

6.2.2 Subject Preparation

For a detailed summary of the methods, please see Gil Coury *et al.* (1998b). After thorough cleansing of the skin with rubbing alcohol and shaving of hair if necessary, three pairs of bipolar surface electrodes were placed bilaterally above the muscle bellies of the anterior deltoid, the long head of the biceps brachii and over the flexor carpi radialis as described by Gil Coury *et al.* (1998b). An electrode was also placed above the sterno-costal portion of the right pectoralis major, unfortunately bilateral recording of the EMG over this muscle was not permitted due to mechanical problems with one of our electrodes. A ground electrode was then placed above the right acromion. Subjects were permitted to stretch if they desired. They were then familiarized with the task.

6.2.3 Task

The subjects were asked to perform 21 isometric two-handed maximum voluntary contractions. Seven upper extremity positions and three trunk postures were studied. figure 6.1 describes the shoulder positions. The trunk postures tested were neutral, 90° right and 90° left axial rotation. Figure 6.2 depicts a subject in the condition s0e90s, which is shoulder-neutral, elbow flexed to 90° and in the symmetrical trunk posture. The arm positions and trunk postures were verified bilaterally by the principal researcher with a goniometer. Trunk posture was standardized through markings on the floor. The subjects were instructed to align their feet with the angle markings and rotate their trunk

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so that their shoulders were parallel with the force-measuring device (see figure 6.2). The trunk angle was relative to the shoulder position. The subjects were instructed to limit rotation of their pelvis towards the neutral testing position as much as possible by abstaining from excessive rotation of the hips and knees. This would have resulted in a trunk angle less than 90^{o}. The pelvis was not stabilized, however if the subject was observed rotating the pelvis during the trial, the trial was repeated. When the hands were placed on the lateral surfaces of the force-measuring device, the upper extremity was aligned orthogonally with the long axis of the force-measuring device, regardless of arm position. Subjects were instructed to compress the device through its long axis and to maintain their elbow position in the same plane as the hand and shoulder, thus not allowing the elbow to rotate away from the force-measuring device which would have altered the mechanics of the movement.

The force-measuring device (see Gil Coury *et al.*, 1998a & 1998b) was held between the palmar surfaces of the hands while being supported by a moveable platform (Kumar & Mital, 1993). The subjects did not lift the force-measuring device from the platform. The height of the force measuring device was adjusted using the moveable platform according to the anthropometric characteristics of the subjects and the experimental condition (see figures 4.1 & 4.2). Prior to testing, subjects were allowed several practice trials to become familiar with the experimental setup.

Subjects were instructed to gradually build up the force by compressing on the lateral surfaces of the force-measuring device over a 5-second period and then maintain their Maximum Voluntary Contraction (MVC) for an additional 2 seconds. To facilitate this, feedback on force production was provided through an oscilloscope. The force-time curve was presented in real time and the subjects were asked to produce consistent patterns for quality assurance. That is, those trials in which the subject attained MVC too early or late were repeated. The presentation of the conditions was randomized and the subjects had a minimum rest of 2 minutes between trials. The subjects were permitted more time if they requested, however none did.

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6.2.4 Equipment

6.2.4.1 Force-Measuring Device

The specific characteristics of the force-measuring device are provided in two previous papers (Gil Coury *et al.*, 1998a & 1998b). The device consisted of a lightweight aluminum box (see figure 4.2) with compressible lateral sides measuring 40 cm x 20 cm x 20 cm. The lateral sides were not in contact with the rest of the box. A load cell (model SM 500; Interface, Scottsdale AZ USA) was fastened between the lateral sides via two rods. The load cell was held in place using screws and foam filling to prevent any extraneous movement. Prior to testing, the load cell was calibrated in 5lb increments. Raw force values were converted to SI units in analysis of these data.

6.2.4.2 Force-Monitoring Devices

The output of the load cell was input into a force monitor (model ST-1; Prototype Design and Fabrication Company, Ann Arbor, MI, USA) and then to an oscilloscope (model Vc-6050; Hitachi Denshi Ltd. Tokyo Japan). A sweep of 1s/cm was used. The subjects easily viewed the force-monitoring devices.

6.2.4.3 Electromyographic Setup

The EMG electrodes were of the knife edge type (model MDI-X10; Neuromuscular Research Center, University of Boston, MA, USA) and measured 1 cm x 0.5 cm with a 1 cm inter-electrode distance. The electrodes had an on-site gain of 10 and a high pass filter of 6 Hz. The system gain was 1000 to 3000 depending on the channel and the bandwidth was 20 to 500 Hz. The EMG signals were preamplified and input to an isolated amplifier system. The pre-amplifier and amplifier were calibrated within a range of 100 μV to 5 mV. Each EMG channel was calibrated prior to the experiment by feeding a known signal.

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6.2.4.4 *Data Acquisition*

Data were collected on an Intel Pentium class microcomputer through an AD acquisition board model DT 2801-A (Data Translation, Marlboro, MA, USA). Sampling rate was set to 1000 Hz and a time constant of 25 ms was used when converting to the Root Mean Square (RMS) EMG signal.

6.2.5 Force-EMG Analysis

Upon conversion of the raw EMG signals to the Root Mean Square (RMS) EMG signal, customized software (Kumar & Garand, 1991) was used to mark the onset (baseline) and end (point of maximum force) of each trial. Using the point of maximum force value, 20%, 40%, 60% and 80% intervals of MVC were calculated. Then using the force trace as a reference, the time at which these levels occurred was determined. A 0.2 second window around each time point was used to determine the mean and peak EMG values for each respective interval.

6.2.6 Statistical Analysis

The mean and peak force values ± 1 standard deviation (SD) were computed for the total task. The mean force and EMG data over the total task were then submitted to a multivariate analysis of variance (MANOVA) tested against the $\alpha = 0.05$ level of significance as well as *post hoc* multiple comparisons tests (Scheffé comparisons) when a significant F value was noted. Further analysis was performed on the interval data. The five interval levels of MVC were submitted to the same analysis as the total task data. In addition to these analyses, Pearson correlation coefficients were calculated in order to assess the relationship between EMG and force by interval level of MVC.

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6.3 Results

6.3.1 Force

Table 6.1 presents the mean and peak force for each condition. Significant differences between measured upper extremity adduction force during neutral and excessive axial trunk rotation (90° to the left and right) postures were not found.

When these data were collapsed across symmetry, the results were quite similar to those obtained by Gil Coury *et al.* (1998b). Differences between forces produced with respect to each upper extremity position were significant ($p < 0.05$), with the highest mean force being produced when the shoulder was in neutral position and the elbow at an angle of 60° (s0e60) and the lowest when the shoulder was at an angle of 90° and the elbow was neutral (s90e0). Post hoc Scheffé comparisons revealed that only these two conditions were significantly different, yet the relationship was strong enough produce a significant F value when these data were submitted to the MANOVA. With respect to peak force, differences across the group were again significant ($p < 0.01$), yet some additional comparisons were also significant. When collapsed across trunk posture, both the s30e30 and s0e60 upper extremity positions produced significantly greater peak forces than s90e0 ($p < 0.05$). In addition to this, s0e60 was also significantly greater ($p < 0.05$) than s60e0.

When these data were divided into five 20% interval levels, significant differences were noted across conditions and levels ($p < 0.01$). When average force was tested against condition, the results were identical to the peak force collapsed across symmetry ($p < 0.05$), as noted above. When average force was tested against level, all multiple comparisons were significant ($p < 0.05$) and followed similar trends as noted above.

6.3.2 Electromyography

Sample EMG traces for the s0e60s condition (shoulder 0°, elbow 60° in the sagittal trunk posture) are shown in Figure 6.3. The results obtained were similar in

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nature to those reported by Gil Coury *et al.* (1998b). There was a definite trend towards increasing EMG activity for all muscles as each trial progressed, reaching a maximum after approximately 5 seconds, which corresponded to the time that MVC was reached, as noted in figure 6.3. With respect to position, there was also a trend towards increasing EMG activity as the upper extremity was flexed anteriorly, even as force production decreased.

As expected, significant differences were noted across upper extremity positions, EMG activity collapsed across all muscles and when the two were combined ($p < 0.01$) for both mean and peak EMG signal for the total task. No differences were found between different trunk rotation postures. *Post hoc* multiple comparisons revealed where the differences listed above were located, these results are summarized in table 6.2.

With respect to the interval data, significant differences were noted for upper extremity conditions, EMG activity across all muscles and levels ($p < 0.01$). Differences were also noted when upper extremity position was crossed with trunk rotation, interval level as well as EMG activity across all muscles ($p < 0.05$). There were statistically significant differences between EMG activity across all muscles with respect to trunk rotation and interval level ($p < 0.01$).

The most active muscle pairs were the biceps brachii and the flexor carpi radialis, depending upon upper extremity position. With the shoulder in extension (condition s-30e90) on in neutral (conditions s0e60, s0e90 and s0e120), the activity of the flexors was most dominant, followed by the biceps, right pectoralis and deltoids. An example of this observation can be seen in figures 6.3 and 6.4. Interestingly, some differences were noted relative to the direction of axial trunk rotation. In two of four conditions (s-30e90r and s0e90s), the activity of the right pectoralis was greater than biceps and deltoid.

With the shoulder anteriorly flexed the EMG activity was altered. When the shoulder and elbow were flexed to 30^{o}, there was relatively equal contribution by both the biceps and the flexors, with minor contribution from the deltoids and minimal contribution from the pectoralis. The dominant muscle was the biceps in the remaining conditions with an anterior shoulder flexion component (s60e0 and s90e0). The deltoids were the next most active muscle, followed by minimal contribution from the flexors and right pectoralis. There were no differences between trunk rotation under these conditions.

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However, some contralateral differences were noted between left and right flexors. Left flexor carpi radialis activity was consistently less than that of the right, being most pronounced in the s60e0l and s90e0l conditions. During the first two 20% intervals, the muscular activity of the two muscles was similar, however as the subjects reached MVC, there was a trend for the right flexor to have a greater average EMG amplitude.

6.3.3 Force-EMG Relationship

Figures 6.4 and 6.5 depict the force-EMG relationship divided into interval levels of MVC in graphical form with respect to the s0e60 and the s90e0 conditions in three trunk rotations respectively. There was a positive correlation between force and EMG activity, as indicated in figures 4.4 and 4.5. The Pearson correlation coefficients describing the relationship between mean force and average EMG amplitude are presented in table 4.3. These results are similar to those obtained by Gil Coury *et al.* (1998b). In general, the coefficients are low, with a range between 0.226 and 0.825. The left and right biceps as well as the right pectoralis were the most consistent, with the right pectoralis expressing the most correlation between force and EMG activity. Bilaterally, the deltoid and the flexors exhibited particularly low correlation, Gil Coury *et al.* (1998b) reported similar results.

6.4 Discussion

The force results are an estimate of gross upper extremity adduction isometric strength, to maintain continuity the values will be presented and discussed as force (N), however it should be kept in mind that these values represent gross upper extremity strength. The force results obtained in the upper extremity positions as well as the symmetrical trunk posture in the present study are quite similar to those reported by Gil Coury *et al.* (1998b). Tests of homogeneity (Z-score) were performed on the anthropometric data as well as the strength values of the upper extremity positions in the neutral trunk posture in order to compare the two studies and no results were significant, indicating that the two groups of subjects and data were not dissimilar. Similar

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comparisons cannot be made against Gil Coury *et al.* (1998a) due to different testing methods used.

The results confirm earlier claims by Gil Coury *et al.* (1998a & 1998b) that the upper extremity produces the most adduction force when the hands are located relatively close to the body, with some degree of elbow flexion, and as little anterior shoulder flexion as possible. This has direct implications for manual material handling of boxes with poor coupling. As often as possible, where proper engineering controls cannot be employed, materials must be held close to the body to decrease the likelihood of overloading the upper extremity muscles and risk the development of a musculoskeletal injury.

From a biomechanical perspective, it would be expected that the adduction pattern of movement about the shoulder requires rotational torque about the glenohumeral joint. When the humerus is vertical (s0e60 and s0e120), the torque is generated by the deltoid and pectoralis major and when the humerus is horizontal (s60e0 and s90e0), the torque is generated by a 'true' humeral adduction. The biceps brachii would also be active throughout, including the upper extremity positions with combinations of shoulder and elbow flexion.

Statistically, there were no differences found between the measured force as well as the EMG activity and the axial trunk postures tested during the total task. This result is understandable because functionally there is no direct link between the two postures (neutral and rotated 90°). To achieve the 90° axial trunk rotation (relative to the upper extremity) in the present study, the trunk must rotate about the pelvis. Since the feet were fixed, and the subjects were instructed to limit rotation of their pelvis towards the neutral testing position, a natural behavior that would have decreased the axial trunk angle, the movement was assumed to take place via the thoracic vertebral motion. Axial trunk rotation takes place primarily between the thoracic vertebrae and their respective motion segments, each segment accounting for approximately 10° of rotation (White & Panjabi, 1978; Nordin & Frankel, 1989). Thus the only links relevant between the nuetral and rotated axial trunk postures in the present study are the latissimus dorsi muscle, and to a lesser extent the pectoralis major. Although a primary contributor to the adduction pattern

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of movement about the shoulder joint, it was not included in this study due to the insignificant level of activity recorded in preliminary tests (Gil Coury *et al.*, 1998b).

It has been suggested that a biomechanical advantage exists for the latissimus dorsi and the pectoralis major when there is axial rotation of the trunk (Steindler, 1977). In the latissimus dorsi, this advantage is due to an increase in the contribution of the elastic component of muscle associated with axial trunk rotation and the resulting stretch on the muscle. Perhaps this factor accounts for the small increase in mean as well as peak force production that was found in the excessive right axial trunk rotation. This small difference was not found in the left trunk rotation. Nine of the subjects were right hand dominant, hence their right musculature may be capable of developing greater adduction force. This, when, coupled with the biomechanical advantage of the two primary contributors to the adduction pattern of movement in the upper extremity thought to be affected by trunk asymmetry, could account for this small discrepancy. The primary role of the pectoralis major in this movement may also account for the consistent relationship between force and muscular activity.

Biceps brachii activity, due to the biarticular nature of this muscle, was strong in the upper extremity positions when the shoulder was in neutral as well as when it was in anterior flexion. The biarticular muscles alter their behavior as a function of the limb position and task. With the shoulder in the neutral position, the biceps may have contributed more to force than joint stability, whereas when the shoulder was flexed anteriorly, the relative contribution was greater for stability and maintaining the upper extremity position. As the upper extremity was flexed anteriorly, more force must be devoted to maintain the static position to counter the weight vector of the arm.

The relatively low correlation between force and EMG is not surprising. Only four muscles of fourteen believed to contribute to the overall compression of the force-measuring device and the pattern of upper extremity adduction were studied in the present study. Muscles such as teres major, subscapularis, coracobrachialis, brachialis and the pronator teres were probably also contributing in some if not all of the upper extremity positions. In order to achieve greater concordance between force and EMG activity, the activity of all muscles believed to participate in the movement would have to

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be recorded. However even then, this relationship is tentative at best (Kumar & Mital, 1997).

Although this study provides no new information with respect to the force and electromyographic behavior of the upper extremity with respect to position, it does provide evidence to suggest that upper extremity strength is not weakened statistically by *significant* levels of axial trunk rotation. Clinical findings may not follow this pattern. Since the subjects in the manual materials handling simulation did not support the force-measuring device, whether similar findings would be replicated in the field is unknown. One factor that could affect the results is the coefficient of friction between the hand and the material being handled, particularly when no coupling exists. If workers are required to handle material without sufficient coupling, as was replicated in the present study, the worker must produce muscular force much greater than that are normally required to lift the material with proper coupling. With poor coupling, more force is required to maintain a high coefficient of static friction, thus decreasing the overall load bearing capacity of the worker. The material must first be held without slippage, which may require a significant portion of the workers overall upper extremity strength, then the weight of the material as well as the arm must be supported during the handling. This may simply transfer the likelihood of musculoskeletal injury to another location.

Although upper extremity strength is not affected by trunk rotation, risk of injury may simply be transferred to the low back as loads are lifted. It is well established that lifting capacity is reduced when the trunk is axially rotated (Kumar *et al.*, 1995; Kumar 1996). Perhaps the absence of a decrease in upper extremity strength may lead to a sense of false security in manual materials handling tasks. This may result in an increased propensity for injury development in those musculoskeletal structures known to be adversely affected by axial trunk rotation.

6.5 Conclusions

These results confirm the hypothesis that shoulder adduction strength is not significantly affected by trunk rotation, even in large motions. The strength profile of the upper extremity is highly affected by position and those positions where the upper

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extremity is capable of producing the greatest adduction force should be kept in mind in manual materials handling tasks. The EMG activity recorded indicates that the biceps brachii and the flexor carpi radialis are two highly active muscles and these muscles should not be overloaded. Even though axial trunk posture does not affect upper extremity adduction strength, this does not mean that the same loads that can be held in neutral postures can be held in rotated postures as the load may be transferred to other structures, such as the low back, that are more susceptible to decreases in strength relative to axial trunk rotation angle. As a result, the load transfer may lead to an increased risk of musculoskeletal injury development in the low back. Wherever possible, the most appropriate method is still to introduce engineering controls to reduce the likelihood of developing musculoskeletal injuries.

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Table 6.1: The mean and peak force measurement (N) for each condition. n = 10 unless otherwise stated.

Upper Extremity Position	Trunk Rotation	Mean Force (N)	std dev (N)	Peak Force (N)	std dev (N)
S –30° / E 90°	Sagittal	79.14	22.41	120.49	31.16
	90° Right [a]	76.14	18.86	110.63	23.10
	90° Left	74.17	17.40	111.94	26.96
S 0° / E 60°	Sagittal	86.26	23.62	131.40	29.69
	90° Right	86.47	26.21	131.88	32.26
	90° Left [b]	85.37	17.95	131.19	30.48
S 0° / E 90°	Sagittal	72.47	17.03	118.12	26.63
	90° Right	82.67	18.62	119.54	26.13
	90° Left	76.72	14.85	115.74	21.69
S 0° / E 120°	Sagittal	77.12	22.55	114.79	23.93
	90° Right	81.75	24.63	121.91	33.64
	90° Left	71.69	17.66	111.94	22.51
S 30° / E 30°	Sagittal [a]	81.24	25.84	123.28	34.33
	90° Right [a]	80.07	23.46	123.81	32.18
	90° Left [a]	80.20	21.61	123.27	29.39
S 60° / E 0°	Sagittal	68.74	17.22	112.92	21.92
	90° Right	72.69	16.19	104.83	21.33
	90° Left	68.54	20.99	100.56	20.55
S 90° / E 0°	Sagittal	65.78	16.63	100.08	21.34
	90° Right	66.12	17.70	94.86	21.73
	90° Left	64.86	17.63	94.86	23.82

S ; Shoulder angle; neutral position taken as 0°.
E ; Elbow angle; neutral position taken as 0°.

[a] ; n = 9
[b] ; n = 8

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Table 6.2: Results of *post hoc* multiple comparisons analysis of the EMG activity with respect to upper extremity position for the total task by the Scheffé method. n = 10 unless otherwise stated.

Muscle	Significant differences between Upper Extremity Position		Level of Significance	EMG Variable	
				Average	Maximum
Left Biceps	S 0° / E 120°	S 60° / E 0°	0.010	✓	
	S 0° / E 120°	S 90° / E 0°	0.001	✓	
	S 0° / E 60° [b]	S 90° / E 0°	0.016	✓	
	S 0° / E 90°	S 60° / E 0°	0.010	✓	
	S 0° / E 90°	S 90° / E 0°	0.001	✓	
	S 30° / E 30° [a]	S –30° / E 90°	0.015	✓	
	S –30° / E 90° [a]	S 30° / E 30°	0.015	✓	
	S –30° / E 90° [a]	S 60° / E 0°	0.002	✓	
	S –30° / E 90° [a]	S 90° / E 0°	0.001	✓	
Right Biceps	S 0° / E 120°	S 30° / E 30°	0.001	✓	✓
	S 0° / E 120°	S 60° / E 0°	0.006	✓	✓
	S 0° / E 120°	S 90° / E 0°	0.001	✓	✓
	S 0° / E 60°	S 30° / E 30°	0.013	✓	✓
	S 0° / E 60°	S 90° / E 0°	0.011	✓	
	S 0° / E 90°	S 30° / E 30°	0.001	✓	✓
	S 0° / E 90°	S 60° / E 0°	0.001	✓	✓
	S 0° / E 90°	S 90° / E 0°	0.001	✓	✓
	S –30° / E 90°	S 30° / E 30°	0.001	✓	
	S –30° / E 90°	S 60° / E 0°	0.001	✓	
	S –30° / E 90°	S 90° / E 0°	0.001	✓	
Left deltoid	S 0° / E 120°	S 90° / E 0°	0.001	✓	✓
	S 0° / E 60°	S 90° / E 0°	0.001	✓	✓
	S 0° / E 90°	S 90° / E 0°	0.001	✓	✓
	S 30° / E 30°	S 90° / E 0°	0.010	✓	
	S –30° / E 90°	S 60° / E 0°	0.001	✓	
	S –30° / E 90°	S 90° / E 0°	0.001	✓	✓
Right deltoid	S 0° / E 60°	S 90° / E 0°	0.004	✓	
	S 0° / E 90°	S 90° / E 0°	0.006	✓	
	S –30° / E 90°	S 60° / E 0°	0.025	✓	
	S –30° / E 90°	S 90° / E 0°	0.001	✓	

S ; Shoulder angle; neutral position taken as 0°. [a] ; n = 9

E ; Elbow angle; neutral position taken as 0°. [b] ; n = 8

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Table 6.3: Pearson correlation coefficients between mean force measurement and average EMG amplitude for each condition by interval of MVC. n = 10 unless otherwise stated. All correlations significant at the $\alpha < 0.01$ level unless otherwise stated.

Upper Extremity Position	Trunk Rotation	Biceps		Deltoid		Flexors		Pectoralis
		Left	Right	Left	Right	Left	Right	Right
S -30° / E 90°	Neutral	0.572	0.623	0.515	0.619	0.619	0.384	0.802
	90° Right [a]	0.735	0.730	0.438	0.532	0.400	0.502	0.653
	90° Left	0.416	0.445	0.524	0.639	0.538	0.402	0.766
S 0° / E 60°	Neutral	0.531	0.610	0.561	0.441	0.344*	0.399	0.577
	90° Right	0.658	0.448	0.481	0.404	0.551	0.462	0.613
	90° Left [b]	0.789	0.696	0.556	0.583	0.675	0.642	0.746
S 0° / E 90°	Neutral	0.510	0.599	0.614	0.408	0.483	0.662	0.737
	90° Right	0.619	0.489	0.602	0.574	0.543	0.549	0.684
	90° Left	0.538	0.553	0.522	0.679	0.602	0.280*	0.683
S 0° / E 120°	Neutral	0.586	0.576	0.559	0.572	0.509	0.648	0.604
	90° Right	0.670	0.757	0.616	0.483	0.507	0.499	0.667
	90° Left	0.534	0.693	0.509	0.665	0.502	0.678	0.665
S 30° / E 30°	Neutral [a]	0.825	0.751	0.638	0.534	0.465	0.659	0.798
	90° Right [a]	0.696	0.534	0.787	0.378*	0.361*	0.332*	0.714
	90° Left [a]	0.557	0.750	0.539	0.315*	0.459	0.654	0.593
S 60° / E 0°	Neutral	0.702	0.698	0.458	0.544	0.612	0.772	0.677
	90° Right	0.648	0.705	0.429	0.486	0.413	0.801	0.580
	90° Left	0.695	0.609	0.238†	0.593	0.666	0.816	0.623
S 90° / E 0°	Neutral	0.672	0.608	0.445	0.500	0.559	0.629	0.548
	90° Right	0.748	0.707	0.564	0.498	0.643	0.739	0.597
	90° Left	0.708	0.768	0.226†	0.469	0.674	0.657	0.488

S ; Shoulder angle; neutral position taken as 0°.
E ; Elbow angle; neutral position taken as 0°.
* ; $P < 0.05$

[a] ; n = 9
[b] ; n = 8
† ; not significant

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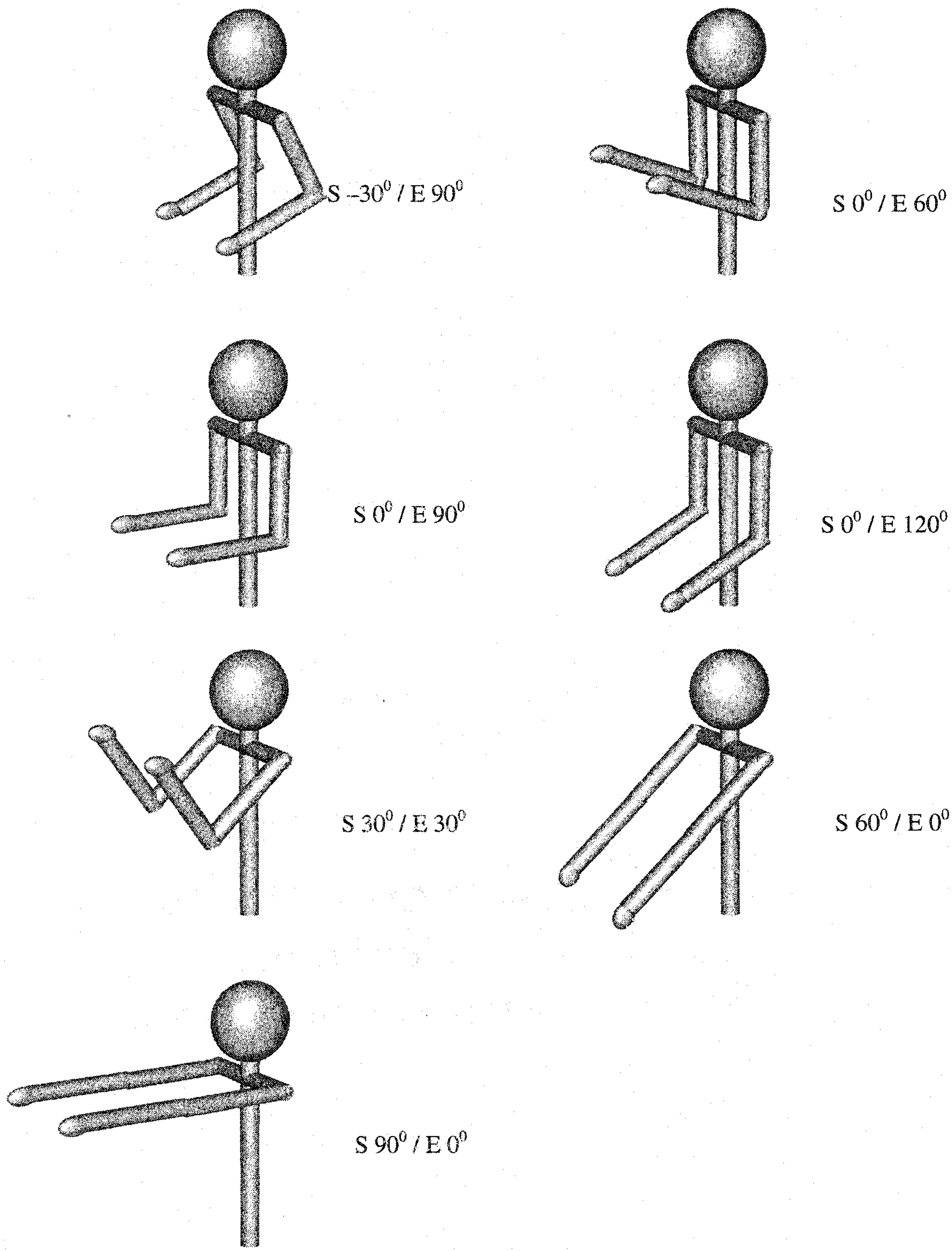

Figure 6.1: Shoulder positions tested.

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Figure 6.2: Example of subject in the s0e90s condition. The shoulder is in the neutral position, the elbow at 90° and the trunk in the neutral position.

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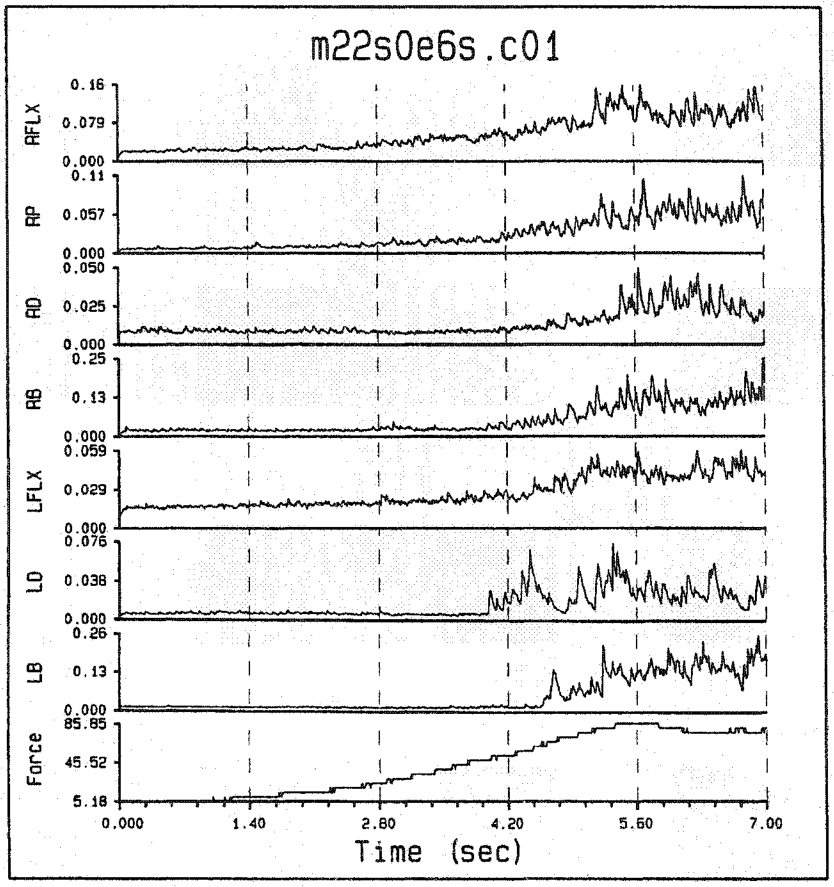

Figure 6.3: Example of recorded muscular activity and force with the shoulder in the neutral position, the elbow at 60° and the trunk in the neutral position.

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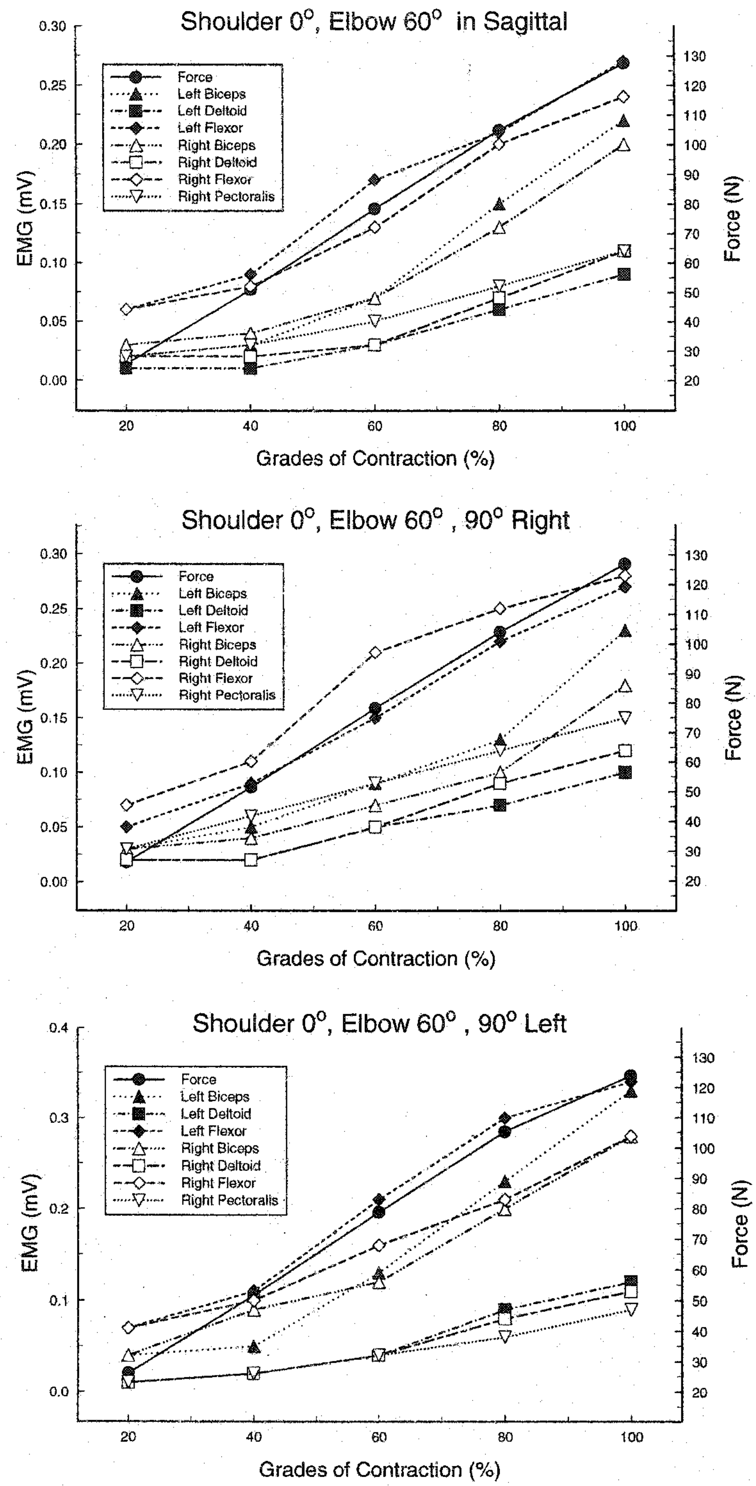

Figure 6.4: The force-EMG activity relationship divided into five 20% intervals of MVC with respect to the upper extremity position that yielded the greatest force values. The shoulder was in neutral and the elbow at 60° in three trunk postures. n = 8.

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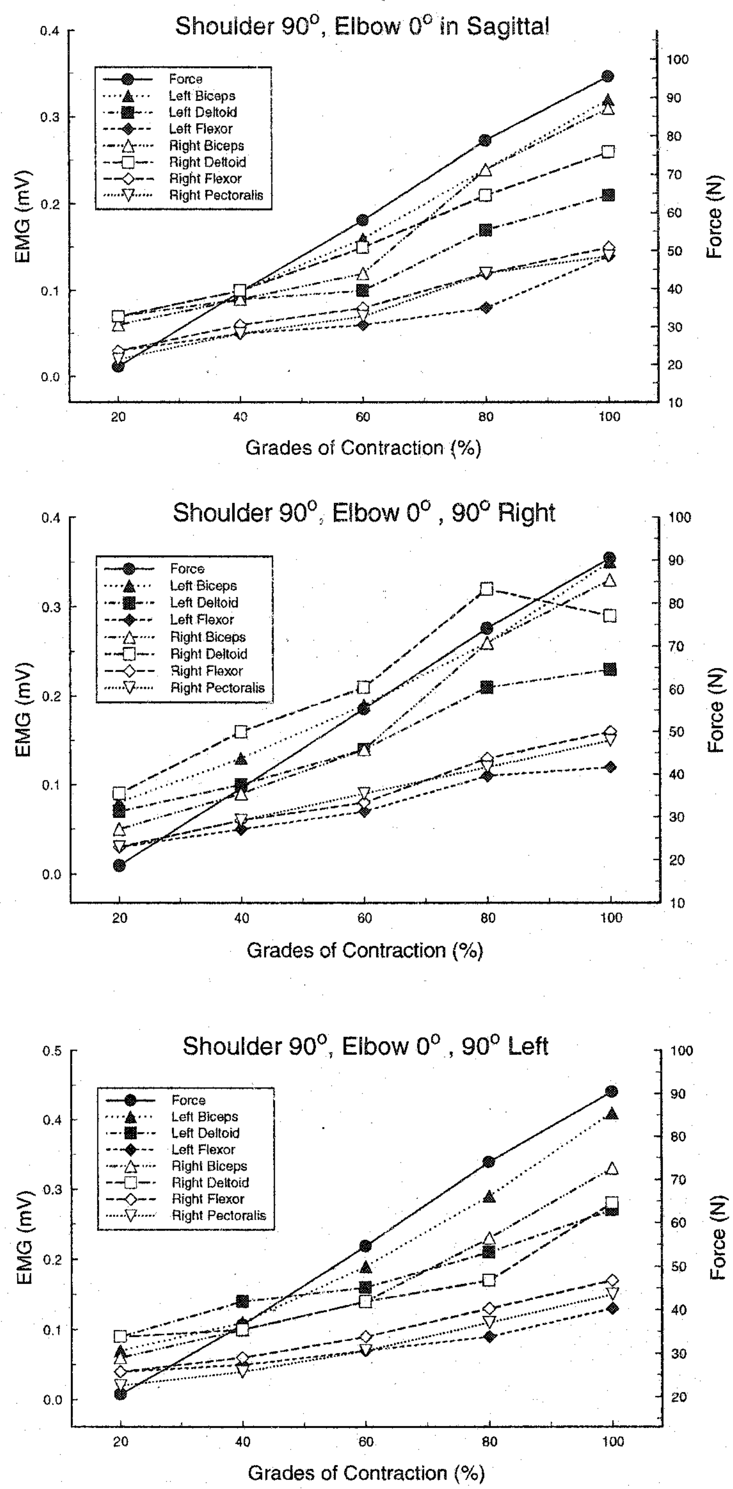

Figure 6.5: The force-EMG activity relationship divided into five 20% intervals of MVC with respect to the upper extremity position that yielded the least amount of force. The shoulder was at 90° and the elbow was in neutral in three trunk postures. n = 10.

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Chapter 7

Maximum Net Tangential Force and Muscular Activity During Industrial Handwheel Actuation[1]

[1] This chapter has been submitted for publication in *Ergonomics*. It is currently in the peer review process. AMELL, T., KUMAR, S., NARAYAN, Y. & SENTHILSELVAN, A. Maximum Net Tangential Force and Muscular Activity During Industrial Handwheel Actuation.

7.1 Introduction

Overexertion and repetitive motion are commonly reported to be the leading causes of compensable occupational injuries and illnesses incurred by industrial workers, particularly those affecting the low back and upper extremity (Keyserling 2000a, b). Although musculoskeletal injury causation is multifactorial in nature (Kumar 2001), it is widely accepted that one of the primary methods to control the incidence and severity of these afflictions is via the reduction of tasks requiring these motions (Marras 2000, Waters *et al.*, 1999, Westgaard and Winkel 1997, Waters *et al.*, 1993). The assessment of worker characteristics in terms of strength, posture, repetitiveness and cumulative load related to the tasks may provide valuable information for control. This information may then be considered in the design or re-design such that the tasks match the capabilities of the worker.

Some hazardous occupational tasks, such as manual materials handling, have been studied extensively for this purpose (Keyserling 2000a, b, Marras 2000, Waters *et al.*, 1993), while other tasks have received less attention in the ergonomic literature. These other tasks may be less prevalent than manual materials handling in an absolute sense, however comparatively a large number of workers may be required to undertake these tasks and hence are exposed to increased risk of overexertion or repetitive motion injury. Industrial handwheel actuation is one such task that has been reported to be hazardous (Amell and Kumar 2001, Parks and Schulze 1998, Woldstaad *et al.*, 1995, Jackson *et al.*, 1992). This task has received comparatively little attention in injury control efforts,

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furthermore the recommended design values that exist are insufficient and irrelevant (Amell and Kumar 2001). Handwheel control devices are used extensively in the control of processes in the petroleum and chemical industries, power generation, waste treatment and transportation (Amell and Kumar 2001, Wood *et al.*, 1999/2000; Schulze *et al.*, 1997, Woldstad *et al.*, 1995). It has been reported that the design of these control devices significantly affects the ability of the worker to actuate the device, and that even well engineered systems will perform ineffectually if the controls are not adequately designed for human use (Raouf *et al.*, 1984, McCormick 1976).

This task requires very large static net tangential forces, usually counter-clockwise while 'opening'. This actuation is commonly referred to as 'cracking' or 'breaking' of the handwheel and usually requires two-hands. When the handwheel begins to rotate (operation), significantly less force is required. In one study of valve handwheel 'cracking' torques in a petroleum refinery, the minimum torque was 100 Nm while the maximum was 225 Nm (Parks and Schulze 1998). Similarly, a torque of 400 Nm was required to operate 93% of valve handwheels in a chemical plant (Jackson *et al.*, 1992). Even with very large handwheels, such high torque demand requires extremely large tangential forces. In addition, the issue is further compounded by handwheels located at positions above the shoulder or below the knee or in cramped spaces, at sub-optimum angles or levels of footing. These design factors combine to form an occupational task that is hazardous to undertake due to the excessive force demands, awkward body postures and high levels of repetition required.

Although sparse, several studies concerning worker capabilities while actuating handwheels have been published. In two similar studies, Schulze *et al.* (1997a) and Wood *et al.* (1999/2000) reported statistically insignificant main effects for handwheel height above the grade in relation to isokinetic torque. Maximum torque values ranged from 30 Nm to 60 Nm for females and males respectively using handwheels from 17 cm to 43 cm in diameter. The difference between the heights tested was 41 cm (Schulze *et al.*, 1997) and 100 cm (Wood *et al.*, 1999/2000). Small sample size limits the ability of these studies to reliably detect differences. In addition, the range of heights of handwheels found in the field significantly exceeds these limits, rendering the applicability of these results to real-world facilities questionable (Parks and Schulze 1998). The reach distance between the

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operator and the handwheel was investigated by Wood *et al.* (1999/2000), and was found to decrease as the distance between the operator and the wheel increased. However, the torque difference was less than 5 Nm and the two distances only differed by 15 cm, a relatively small distance in terms of gross body dimensions. Handwheel pitch angle was also studied (Wood *et al.*, 1999/2000) and no difference was found between angles of 0° and 90°.

Woldstad and McMulkin (Woldstad *et al.*, 1995, McMulkin and Woldstad 1995) defined population isometric capabilities for a vertically oriented handwheel turning task at a low height relative to operator stature as well as examined the effects of handwheel rim design on tangential force production. Maximal net tangential forces ranged from 235 N to 614 N for females and males respectively. The authors concluded that grip strength plays a significant role in tangential force production and that existing standard handwheel rim shapes (typically smooth edged) do not permit maximal force development. A zig-zag shaped rim permitted the production of 54% more isometric force than the standard rim.

Several questions regarding worker capabilities in relation to the handwheel actuation task remain unanswered. The effect of above the shoulder and below the knee handwheel heights upon the operators' ability to generate a maximum tangential force has not been studied, nor has distance of foot support. Furthermore, the effect of contour of foot support has not been studied in the past. Finally, and perhaps most importantly, no studies of handwheel actuation have incorporated the level of muscular activity (using electromyography) into the experimental design and hence the contribution of the representative muscles to this task is not known.

The purpose of this study was to determine the maximum two-handed net tangential handwheel force and electromyographic activity of the primary muscles contributing to the task during actuation at various heights, pitch angles, contours of foot support and distances of foot support.

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7.2. Methods

7.2.1 Participants

Twenty healthy males who reported no musculoskeletal injuries at the time of the experiment participated in the study. The study was approved by the University Research Ethics Board. The participants were recruited from the general population of students at the University, and all signed an informed consent document. The participants were required to complete the PAR-Q questionnaire to assess their fitness for physical work (Shephard 1988). All participants were compensated at a rate of $10 per hour. The mean age, weight and height of the sample was 24.2 ± 2.7 years, 75.5 ± 8.5 kg, and 178.8 ± 6.1 cm. Two of the participants were left hand dominant.

7.2.2 Participant Preparation

Bipolar EMG electrodes were placed over the muscle bellies of the erector spinae at the L4 vertebral level, the flexor carpi radialis, biceps brachii, and the anterior deltoid bilaterally (figure 7.1). The skin was thoroughly cleansed with rubbing alcohol and hair removed by shaving when necessary prior to attaching the EMG electrodes. A ground electrode was placed above the right acromion. The electrode leads were input into the amplifier packs worn on the worker's belt. The participants were given warm up exercises prior to the experimental tasks.

7.2.3 Equipment

7.2.3.1 Force Measurement

The force measurement equipment consisted of a handwheel mounted to a shaft housed within a gear assembly (figure 7.2). The handwheel characteristics are listed in table 7.1. The gear assembly was mounted on a sturdy platform. This platform could be raised or lowered. Through a simple beveled gear mechanism, an attempted rotation of

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the handwheel, when it was in the locked position, resulted in a direct linear tensile load being applied to a securely fixed load cell (Omega Type S load cell, model LCCB-1K, Omega Engineering, Stamford, CT, USA). The force measuring system was calibrated using known weights suspended from the handwheel. The load cell output was input into a signal conditioner which in turn was connected to the data acquisition system.

7.2.3.2 Electromyography

The eight bipolar EMG electrodes were of the single differential knife edge type (Bagnoli-8 EMG System; Delsys Inc., Boston, MA, USA) and measured 1 cm x 1 mm with a 1 cm inter-electrode distance. The electrodes had a preamplification of 10, the system gain was 1000, and the bandwidth was 20 to 500 Hz. The preamplified EMG signals were input to an isolated amplifier system. The output of the EMG signals from the amplifier system was input into the interface box and power supply, and then ultimately input into the AD converter on the data acquisition system.

7.2.3.3 Data Acquisition

The data acquisition system consisted of an AD board model DT 2801-A (Data Translation, Marlboro, MA, USA) connected to an Intel Pentium class desktop computer. Sampling rate was set to 1000 Hz and custom-written data acquisition software was used to capture data. A schematic diagram depicting the data acquisition flow is provided in figure 7.3.

7.2.4 Tasks

The experiment was divided into two phases, the first involved standard tests to determine the participants' maximal voluntary contraction (MVC) to be used in the normalization of the EMG signal while the second consisted of the experimental conditions.

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7.2.4.1 Strength Tests for EMG Normalization

The normalization of the EMG signal was accomplished through the use of three maximal effort isometric strength tests. The first of these tests was of bilateral power grip for the flexor carpis radialis using a Jamar hand grip dynamometer (Asirnow Engineering, Los Angeles CA, USA).

All participants were seated with the shoulder in the neutral position, and the forearm flexed to 90° while resting comfortably on the arm of a chair. Participants were instructed to gradually increase their effort over 2 seconds, after which they were to be exerting their maximum force. They were to hold this maximal effort for 3 additional seconds. The second test was of arm strength for the biceps brachii whereby the participants stood on a platform and pulled vertically on a handle attached to a firmly fixed steel chain using both hands. The participants were instructed to limit the force generation to the arms. The shoulder was in the neutral position, and the forearm angle was 90°. In the path of the chain was a load cell (Omega Type S load cell, model LCCB-1K, Omega Engineering, Stamford, CT, USA). The third test was of maximum effort stoop lift strength for the erector spinae whereby the participants pulled vertically on the aforementioned handle attached to the chain and platform using both hands. The same instructions concerning the length of the trials and gradual increase of force used in the grip strength tests were applicable to the arm and stoop strength tests. All strength based EMG normalization tests were replicated 3 times and the mean of these trials was used in all subsequent analyses. The mean static left and right grip strengths, arm, and stoop strengths were 441 ± 62 N, 478 ± 68 N, 372 ± 81 N and 620 ± 209 N respectively.

Since no isometric strength test could be performed for the normalization of the anterior deltoid muscle activity, these data were normalized against the experimental condition resulting in the greatest amount of EMG activity. This analysis was performed post hoc against the conditions when the pitch angle was 0°, the participants stood on a convex surface at a support distance of 19 cm and a handwheel height of 168 cm for the left and when the pitch angle was 90°, the participants stood on a flat surface at a support distance of 19 cm and a handwheel height of 168 cm for the right.

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7.2.4.2 *Experimental Design*

The experimental conditions consisted of the participants being asked to produce three maximal-effort static counter-clockwise exertions on a custom-built handwheel force measuring device under twenty-four experimental conditions in a random order (figure 7.4). In total, four independent experimental variables were examined. These independent variables consisted of 2 handwheel pitch angles (90° and 0° with respect to the horizontal); 2 contours of foot support (flat and convex); 2 distances of foot support (19 cm and 58 cm); and 3 handwheel heights (35, 93 and 168 cm from the grade). The contours of foot support consisted of a rubberized mat on a flat surface that simulated optimum flooring while a convex PVC pipe with a diameter of 28 cm (10 inches) simulated sub-optimum flooring. The distances of foot support were delineated using markers on the floor that the participants' aligned the centre of their foot with, and markers to aid in the placement of convex PVC pipe base.

The participants were permitted to grip the handwheel at any point on the circumference they desired, however they were not permitted to grip the handwheel spokes. The participants were encouraged to familiarize themselves with each posture prior to the recorded trials. The participants were also encouraged to choose a posture that they believed would permit them to produce their maximum net tangential static force upon the handwheel. The participants were required to maintain the same posture and grip configuration for all three recorded trials; they were permitted to rest in between trials.

A minimum of 2 minutes rest was provided after each effort. The highest net tangential force recorded (dependent variable) was referred to as maximum and subsequently used in all analyses. Feedback on the progress of the exertion was provided to the participants via a computer monitor placed in easy view of the participant. Real time force traces were displayed such that the participant could gauge the performance of the trial.

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7.2.5 Analysis

Custom-written software was used to determine the maximum net tangential force exerted upon the handwheel as well as the EMG activity. The maximum net tangential force observed during the three experimental trials was subject to analysis using the coefficient of variation (CV) to determine the agreement between the trials. Raw EMG signals were converted to Root Mean Square (RMS) EMG signal using a time constant of 25 ms then normalized. These data were subjected to repeated measures Analysis of Variance (ANOVA) using SPSS version 10 (SPSS Inc., Chicago, IL, USA). This analysis was carried out in order to determine whether significant main and interaction effects existed, as indicated by Pillai's test due to the four independent factors (pitch angle, contour of foot support, distance of foot support and handwheel height) upon the dependent factors of maximum net tangential handwheel force and maximum normalized EMG activity. The α level was set to 0.05 for determining the significance of Pillai's test.

7.3 Results

7.3.1 Force

The mean CV among the 20 participants across all 24 experimental conditions was 6.54% while the minimum and maximum values were 4.26% and 9.59% respectively. Table 7.2 lists the mean, standard deviation, standard error of the mean, maximum, and minimum forces as well as the torque data for all experimental conditions. The individual forces ranged from 220 N to 1360 N while the mean forces ranged from 585 N to 760 N. The experimental condition in which the participants produced the greatest force involved a pitch angle of 90°, a flat contour, a 58 cm distance of support and a 168 cm height, while the second greatest force was associated with this basic condition only with a convex contour of foot support. The least force was recorded with a pitch angle of 0°, a flat contour, a 19 cm distance of support and a 168 cm height. The same condition with a change of handwheel height to 35 cm produced the second least amount of force.

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The participants could generate more force when the handwheel was oriented at a pitch angle of 90°, however this difference just failed to be significant ($p = 0.054$). The contour of foot support did not effect the level of force ($p = 0.976$), however the distance of foot support did ($p = 0.007$). More force could be generated at the 58 cm distance than at the 19 cm distance. Less force could be generated at the 93 cm height than at the 35 or 168 cm heights, however these results were not statistically significant ($p = 0.167$).

There was significant two-way interaction between the independent factors (table 7.3). Significantly less force was generated when the handwheel pitch angle of 0° was interacted with the distance of foot support of 19 cm. With respect to the interaction between angle and height, the greatest amount of force was generated at an angle of 90° and a height of 168 cm while the least amount of force was generated at an angle 0° at the same height.

The force results obtained are 15-20% greater than those reported by Woldstad *et al.* (1995), however due to the asymmetric task used in their study, this difference is expected. Even though various diameter handwheels were used by Schulze *et al.* (1997) and Wood *et al.* (1999/2000), the largest approximates the handwheel used in the present study. The maximum torque values obtained were around 60 Nm, given a wheel diameter of approximately 41 cm, this equates to roughly 300 N of net tangential force, significantly less than that observed in the present study as well as that reported by Woldstad *et al.* (1995). The present results were more than double, and the results of Woldstad *et al.* (1995) were 80% greater than those obtained by Schulze *et al.* (1997) and Wood *et al.* (1999/2000).

7.3.2 Electromyography

Table 7.4 lists the normalized EMG activity for each muscle, sorted by experimental condition. The flexor carpi radialis muscle (LFLX and RFLX) was the most active. The mean normalized values obtained for this muscle were over 200% that of the static strength tests (MVC), with 100% representing the maximum EMG during the strength test. The next most active muscle was the erector spinae at the L4 lumbar level (LL4 and RL4). This muscle was followed by the anterior deltoid (LDT and RDT) at

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approximately 70% and finally the biceps brachii (LBCP and RBCP) at approximately 45%. The observed activity of the BCP was approximately 20% that of the FLX. The experimental condition eliciting the greatest amount of normalized EMG activity in both the FLX and the erector spinae at the L4 level was at a pitch angle of 90°, a flat surface contour, 58 cm support distance and 35 cm height.

Figure 7.5 illustrates the mean normalized EMG for the four independent factors. The 90° pitch angle orientation was associated with greater normalized electromyographic activity, however this mean difference was not statistically significant ($p = 0.069$). The flat contour of foot support was associated with greater EMG activity ($p = 0.004$). The 58 cm support distance induced more EMG activity and the 35 cm height induced more activity than either the 93 or 168 cm heights (none significant). As expected, the main effect of muscle was statistically significant ($p < 0.001$).

Significant two-way interactions were observed for the EMG data (table 7.5). When the interaction between angle and muscle was investigated, LFLX activity was greatest in the 0° pitch angle (250% of EMG at MVC), although the mean difference was minimal, less than 30%. Conversely, the RLFX activity in the 90° pitch angle orientation was over 100% that of the 0° orientation, 240% versus 140% of EMG at MVC. Similarly, the RL4 activity in the 0° orientation was nearly half, 80% versus 150% that observed in the 90° angle. The normalized EMG activity of the RL4 with respect to this angle was greatest at the 35 cm height and least at the 168 cm height, 140% versus 90%, while the activity of the LL4 did not vary significantly with handwheel height.

7.4 Discussion

Since the CV values were low, this indicates acceptable agreement among the three trials, and confidence may be placed in the data as they are believed to indeed be representative of the maximum force production capability of the participants.

One possible reason for the discrepancy between the results obtained in this study and those previously reported is the equipment utilized. A load cell was used in the present study and Woldstad *et al.* (1995) used a force platform to measure static forces. Schulze *et al.* (1997) and Wood *et al.* (1999/2000) used a commercially available

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isokinetic dynamometer. Although no angular velocities were reported, clearly the dynamic nature of this task design significantly decreased the torque production capabilities of the operators. As a result, the ability of these studies to predict the true static 'cracking' forces required to actuate industrial handwheels is limited, as the dynamic forces are typically well below the static forces observed in the field. Nevertheless, these studies are applicable to those handwheels requiring excessive dynamic forces to operate the control device.

The lack of relationship between handwheel pitch angle and maximum force is in accordance with those results reported by Schulze *et al.* (1997). However, it was hypothesized that the two angles would permit different levels of force generation due to the relationship between upper extremity biomechanics and the task of handwheel actuation. During this task, the combined motion of opposing static tangential forces upon the handwheel resulted in the net counter-clockwise effort measured by the load cell. In the 90° position, this force could have been augmented somewhat by extension of the lower extremity, plantarflexion of the feet or by a left-effort of the torso, though no evidence of this is presented here. The relative contribution of these muscle groups is not known, however since posture did not change significantly over the trial, the effect may be of stabilization. It was thought that the motions in the vertical plane may permit more force to be generated than the push-pull movements associated with the horizontal plane actuation since elbow flexion strength is greater than extension strength (Chaffin and Andersson 1991) and pulling strength is greater than pushing strength (Kumuar 1995, Kumar *et al.* 1995). In the 0° position, the right hand pushes away from the body through the extension at the elbow and flexion at the shoulder while the left hand pulls towards the body through the flexion at the elbow and extension at the shoulder. In the vertical task, the torso and lower body could have augmented the force capability through an upwards effort via the right hand, while in the horizontal task, these regions could have augmented the capability through a rearward effort acting through the left hand. These combined efforts may have canceled out one another and led to the observation of no discernable difference between forces obtained at either pitch angle. The only method of alleviating this would have been to restrict motion of the lower extremity and trunk;

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however such an experimental design would have lost all external validity and would not have been applicable to the design of industrial handwheels in the field.

The two-way interaction effects (table 7.3) of angle*distance and angle*height support the hypothesis described above. With respect to angle*distance, the combination of the 0° angle and 19 cm distance of foot support resulted in significantly less force, this is presumably due to the disadvantageous upper extremity position (constrained) and the inability to use the body weight sufficiently to augment the force generation. Similarly with respect to the highest height, at the 90° angle, the body weight can easily add to the tangential force acting downwards through the left hand while the right hand continues to push upwards. At the lowest handwheel height in this same plane, the powerful lower extremity may have acted to augment the right handed effort to push upwards on the handwheel.

The lack of statistically significant difference between force generation and the main effect of contour of foot support is not surprising as this variable may have had little impact, other than balance and angle of body inclination upon the motions and force generating capability of the upper extremity. Conversely, the lack of difference between handwheel heights is surprising. It would be expected that different heights would permit the participants to exert different amounts of force (Kumar *et al.*, 1995), however as noted above, body weight and lower extremity contribution had the potential to aid the efforts at both the lowest and highest handwheel heights. As a result, the disadvantageous positions and the related decreases in upper extremity strength associated with the lowest and highest heights may have been offset by the contribution of these other muscle groups which could have resulted in maximal tangential forces that did not differ significantly from one another.

The muscular activity observed is in agreement with the reasoning noted above concerning the motions of the relevant body segments. However since EMG was not recorded for all of the muscles that may have contributed to the activity, significant levels of cocontraction may have been present as a result. Future studies of handwheel actuation should include the activity of the triceps brachii and latissimus dorsi to address this issue.

The observation of that the flexor carpis radialis is the most active muscle supports the results of Woldstad *et al.* (1995) and McMulkin and Woldstad (1995) who

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reported that grip strength plays a pivotal role in handwheel actuation. This is due to the notion that this muscle is a primary contributor to grip strength. Since the hands must forcefully grip the handwheel regardless of position or posture in order to exert the tangential force required for actuation, this finding is not surprising. The erector spinae at the L4 vertebral level also exhibited significant activity, which is presumably indicative of the stabilization of the torso required to exert the upper extremity maximally as well as maintain the inclined torso angle at the middle and lowest handwheel heights, particularly in the 0° degree pitch angle orientation. In addition, the activity of this muscle is in agreement with the rationale provided above and that the most activity was observed at the lowest handwheel height and the least in the highest handwheel height. These two muscle groups and their associated body regions may represent those most likely to be affected by overexertion or repetitive motion injuries as a result of industrial handwheel actuation.

The activity of the anterior deltoids indicates that these muscles were recruited to near maximal levels and hence contributed to this task, particularly at higher handwheel heights. The lack of significant amounts of activity in the biceps brachii may be indicative of a supporting or stabilizing role. This muscle may have acted to maintain the upper extremity posture while the flexor carpis radialis maintained the grip and the anterior deltoid, in combination with the torso effort (or lower extremity activity) produced the static exertion upon the handwheel.

The observation that some muscles exhibited activities much greater than they had in the normalization strength tests is probably due to the differences in EMG activity as a result of the length-tension relationship of skeletal muscle. During the static tests, standardized postures were assumed by the participants, and the task required postures that were different. Also, the functional nature of the task may have contributed to greater levels of exertion by the participants. Nevertheless, the normalization of the electromyographic signal did prove to be an invaluable tool in the assessment of the muscular activity.

The results indicate that the task requires significant amounts of physical exertion in order to develop the large static net tangential forces required to actuate handwheels. The overwhelming majority of operators in process plants are middle-aged males who

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may not be capable of exerting forces levels they once did since force production decreases with age (Voorbij and Steenbekkers 2001). Even younger male workers or females may not be able to generate sufficient tangential forces to 'crack' these handwheels, as the maximal effort torques produced on the standard sized wheel used in this study were well below those required to actuate handwheels in the field. Thus, process facility designers, as well as those other industries which rely heavily upon handwheel control devices to regulate systems must be cognizant that there is an upper limit to the amount of tangential force that can be safely developed by the operator, and that required forces should be significantly below 700 N, regardless of handwheel diameter. Ideally, large diameter handwheels should be used in order to decrease the amount of tangential force required. However, due to space and other concerns, this cannot always be accomplished and hence handwheels must be designed within the anthropometric limits of the operator.

Since both above the shoulder work, which requires excessive amounts of forward flexion of the shoulder and below the knee work, which requires excessive amounts of forward flexion of the torso are associated with increased risk of musculoskeletal injury, handwheels located at heights between these levels are preferred. Furthermore, since a vertically orientated handwheel is not as affected by height as a horizontally orientated handwheel, this design is preferable. Such a design allows the operator to use the effective force of gravity to a greater extent.

There is one limitation to this study that must be acknowledged. Gloves were not worn by the participants, and hence these force values may underestimate the true force generating capabilities of this sample as gloves may serve to increase the static coefficient of friction thereby contributing to the force exerted through the hands. This factor had the potential to effect the magnitude of the forces exerted, but not the movement patterns or the electromyographic activity of those muscles observed.

7.5 Conclusions

The industrial handwheel design variables studied altered the tangential force generating capability of the operator as well as the electromyographic activity of the

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muscles contributing to these forces. These results suggest that the operators cannot exert more than 700 N of tangential force, hence safe levels of exertion should reside well below this value. In order to maximize handwheel 'cracking' torques; large diameter handwheels should be used and biomechanical logic dictates that a 90° pitch angle orientation is more appropriate than a 0° pitch angle. Furthermore, the flexor carpis radialis and erector spine are two very active muscle groups during handwheel actuation, and as a result they may represent the most likely structures to be adversely affected by overexertion or repetitive motion injuries.

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Table 7.1: Relevant characteristics of the handwheel used in the experiment. All handwheel values are effective values from the centre of the grip.

Variable	Characteristic
Handwheel	
Radius (r)	21 cm (8 inches)
Diameter (d)	42 cm (16 inches)
Circumference	132 cm (51 inches)
Grip of Handwheel	
Grip Radius	1.5 cm (0.6 inches)
Grip Diameter	3 cm (1.2 inches)
Grip Circumference	9.5 cm (3.7 inches)
Material	Cast iron
Number of Spokes	5
Grip Surface	Knurled edges, hollow back

Table 7.2: Mean, standard error of the mean (SEM), maximum, minimum and moment of force values for each experimental condition. Values in parenthesis represent the standard deviation.

Angle	Contour	Distance	Height	Mean (N)	SEM (N)	Max. (N)	Min. (N)	Moment (Nm)
90°	**Flat**	**58 cm**	**35 cm**	678 (167)	22	1106	266	142 (35)
			93 cm	641 (137)	18	876	293	135 (28)
			168 cm	760 (188)	24	1228	484	159 (39)
		19 cm	**35 cm**	754 (189)	24	1174	317	158 (39)
			93 cm	629 (120)	15	865	287	132 (25)
			168 cm	729 (181)	23	1217	403	153 (38)
	Convex	**58 cm**	**35 cm**	655 (159)	21	1116	284	137 (33)
			93 cm	661 (136)	18	907	296	139 (28)
			168 cm	754 (190)	25	1143	266	158 (39)
		19 cm	**35 cm**	693 (157)	20	1175	376	145 (33)
			93 cm	641 (124)	16	846	363	135 (26)
			168 cm	720 (171)	22	1133	270	151 (35)
0°	**Flat**	**58 cm**	**35 cm**	754 (168)	22	1232	399	158 (35)
			93 cm	680 (177)	23	1103	315	143 (37)
			168 cm	659 (122)	16	891	425	138 (25)
		19 cm	**35 cm**	621 (148)	19	987	359	130 (31)
			93 cm	691 (185)	24	1204	377	145 (38)
			168 cm	585 (137)	18	844	342	123 (28)
	Convex	**58 cm**	**35 cm**	717 (141)	18	1078	440	151 (29)
			93 cm	719 (156)	20	1247	392	151 (32)
			168 cm	645 (145)	19	935	330	135 (30)
		19 cm	**35 cm**	640 (161)	21	1085	222	134 (33)
			93 cm	707 (160)	21	1109	367	148 (33)
			168 cm	631 (141)	18	1006	302	132 (29)

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Table 7.3: Significant two-way interactions for the independent factors of pitch angle, contour of foot support, distance of foot support, height and trial on the maximum net tangential force. Based upon the outcome of a repeated measure ANOVA using Pillai's test and an α level of 0.05.

	Two-way Interaction				
Variable	**Angle**	**Contour**	**Distance**	**Height**	**Trial**
Angle	-				
Contour		-			
Distance	0.001		-		
Height	0.001	0.016		-	
Trial	0.001			0.007	-

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Table 7.4: Mean normalized EMG activity for the erector spinae at the L4 lumbar level, flexor carpi radialis, biceps brachii and the anterior deltoid. Values in parenthesis represent the standard deviation.

Angle	Contour	Distance	Height	Erector Spinae		Flexor Carpi Radialis		Biceps Brachii		Anterior Deltoid	
				Left	Right	Left	Right	Left	Right	Left	Right
90°	Flat	58 cm	35 cm	71 (35)	226 (656)	190 (148)	346 (253)	18 (21)	77 (37)	82 (65)	78 (49)
			93 cm	79 (35)	165 (534)	189 (192)	313 (231)	26 (41)	92 (33)	53 (51)	101 (107)
			168 cm	60 (31)	155 (558)	274 (238)	138 (116)	63 (35)	24 (24)	96 (95)	100 (27)
		19 cm	35 cm	69 (29)	177 (516)	181 (138)	267 (275)	27 (23)	82 (39)	114 (128)	45 (51)
			93 cm	93 (85)	138 (410)	136 (136)	322 (254)	12 (17)	96 (45)	73 (77)	47 (39)
			168 cm	88 (125)	114 (445)	334 (276)	141 (139)	79 (37)	45 (33)	86 (81)	110 (108)
	Convex	58 cm	35 cm	66 (29)	194 (569)	183 (118)	314 (247)	22 (25)	77 (30)	109 (107)	71 (42)
			93 cm	83 (41)	168 (602)	164 (128)	314 (261)	18 (19)	100 (44)	54 (65)	107 (113)
			168 cm	57 (25)	153 (561)	253 (182)	121 (91)	60 (30)	23 (22)	102 (77)	104 (52)
		19 cm	35 cm	83 (61)	97 (290)	179 (139)	188 (159)	15 (17)	79 (41)	121 (153)	50 (60)
			93 cm	93 (72)	62 (80)	144 (116)	336 (284)	16 (21)	96 (43)	63 (50)	47 (44)
			168 cm	63 (21)	121 (498)	310 (273)	110 (77)	78 (36)	45 (30)	81 (68)	92 (30)
0°	Flat	58 cm	35 cm	67 (58)	128 (446)	227 (195)	170 (233)	59 (31)	17 (18)	77 (65)	83 (37)
			93 cm	63 (33)	153 (485)	227 (175)	157 (161)	54 (33)	29 (25)	47 (97)	83 (75)
			168 cm	57 (24)	46 (89)	304 (233)	113 (82)	68 (37)	19 (23)	97 (47)	71 (39)
		19 cm	35 cm	61 (27)	80 (321)	249 (210)	156 (166)	64 (32)	35 (28)	61 (97)	93 (81)
			93 cm	73 (29)	49 (30)	255 (179)	157 (196)	54 (31)	36 (31)	45 (85)	87 (47)
			168 cm	98 (171)	67 (130)	301 (228)	148 (347)	76 (38)	16 (20)	65 (91)	89 (71)
	Convex	58 cm	35 cm	63 (40)	160 (557)	222 (202)	165 (170)	57 (33)	20 (14)	108 (106)	96 (464)
			93 cm	69 (66)	158 (468)	208 (156)	129 (99)	56 (28)	17 (12)	79 (98)	65 (73)
			168 cm	61 (32)	46 (109)	272 (230)	114 (66)	69 (39)	21 (28)	100 (36)	67 (48)
		19 cm	35 cm	63 (34)	56 (105)	191 (158)	143 (120)	55 (32)	26 (22)	76 (142)	89 (68)
			93 cm	64 (26)	45 (32)	228 (184)	148 (161)	60 (36)	23 (19)	35 (56)	70 (36)
			168 cm	59 (23)	44 (26)	300 (213)	107 (168)	70 (40)	14 (16)	89 (108)	62 (34)

Table 7.5: Significant two-way interactions for the independent factors of pitch angle, contour of foot support, distance of foot support, height and trial on the maximum normalized EMG. Based upon the outcome of a repeated measure ANOVA using Pillai's test and an α level of 0.05.

	Two-way Interaction					
Variable	**Angle**	**Contour**	**Distance**	**Height**	**Muscle**	**Trial**
Angle	-					
Contour		-				
Distance			-			
Height				-		
Muscle	0.001	0.001		0.004	-	
Trial					0.007	-

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Figure 7.1: Electrode placement.

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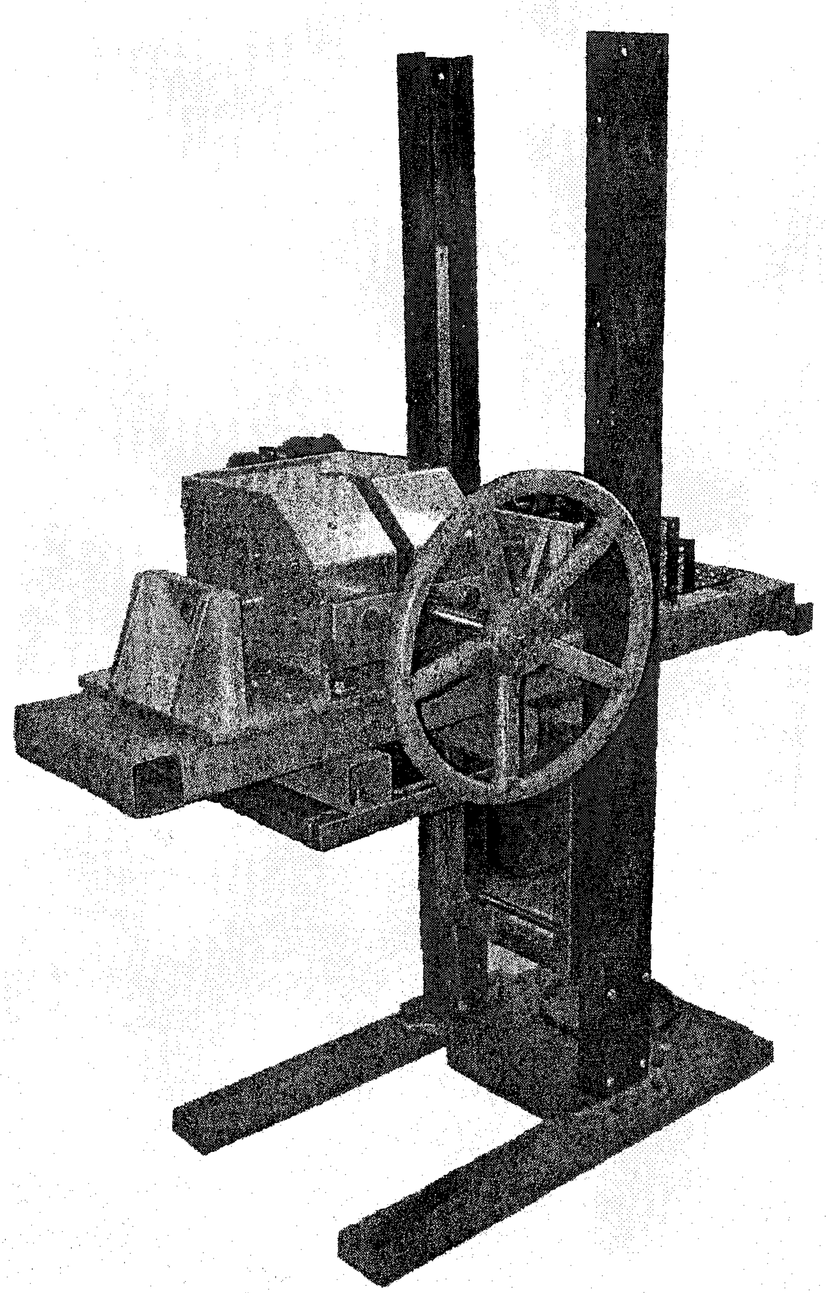

Figure 7.2: Handwheel force measuring device.

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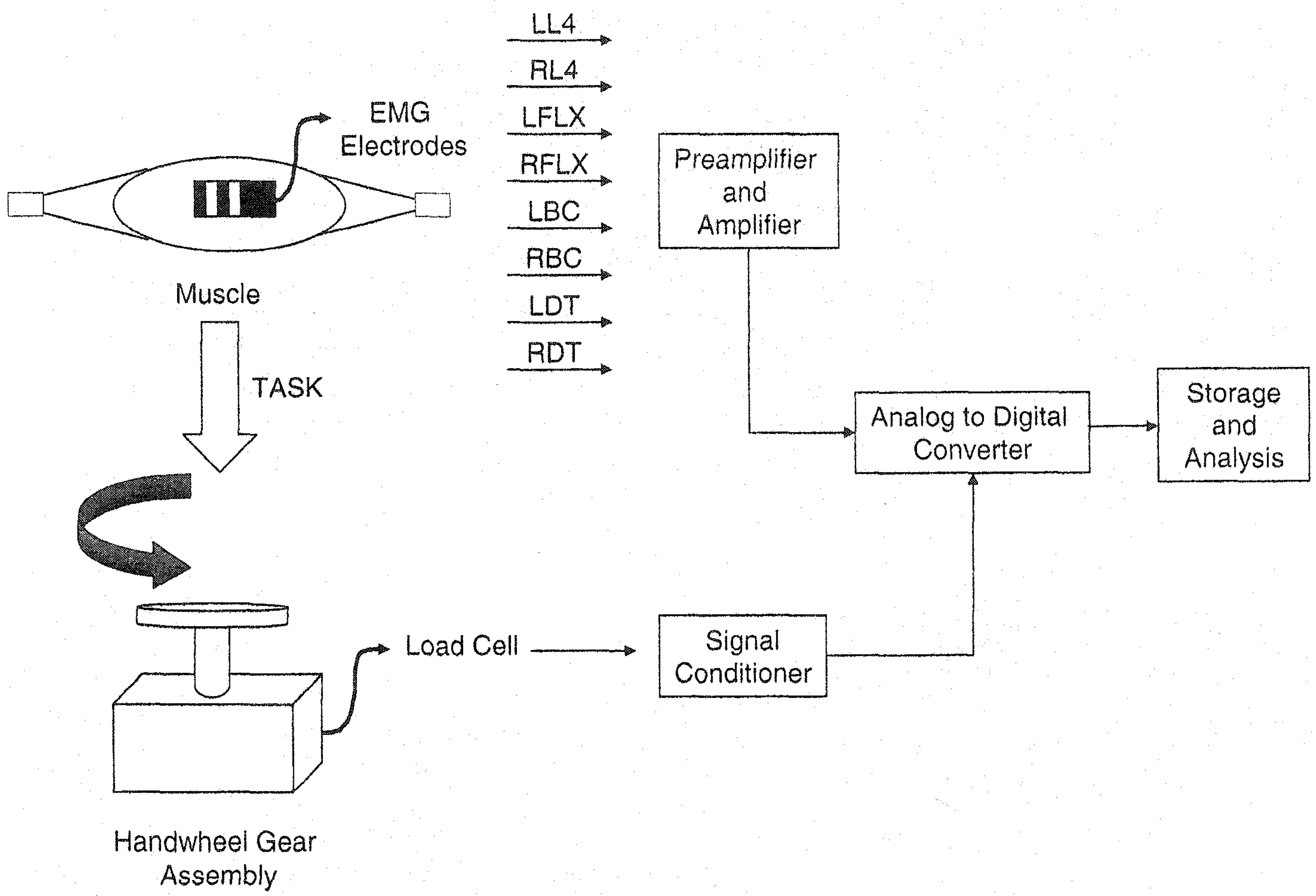
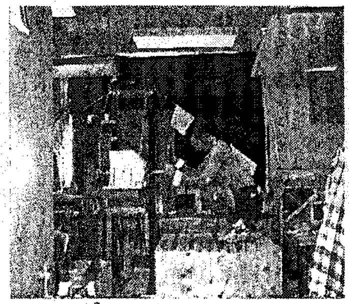
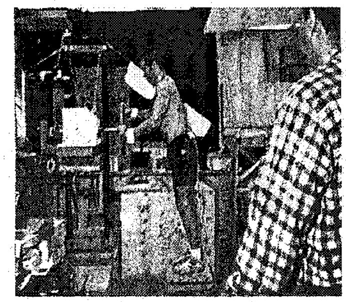


Figure 7.3: Schematic diagram of data acquisition flow. LBCP = Left Bicep; LDT = Left Deltoid; LFLX = Left Flexor Carpi Radialis; LL4 = Left Erector Spinae at the fourth Lumbar Vertebrae; RBCP = Right Bicep; RDT = Right Deltoid; RFLX = Right Flexor Carpi Radialis; RL4 = Right Erector Spinae at the fourth Lumbar Vertebrae.

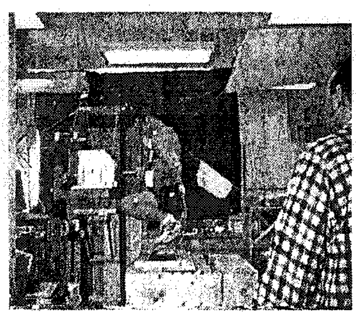


A. 90° Angle, Flat Surface,
58 cm Distance, 35 cm Height

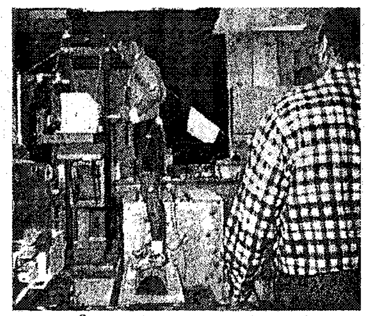


B. 90° Angle, Flat Surface,
58 cm Distance, 93 cm Height

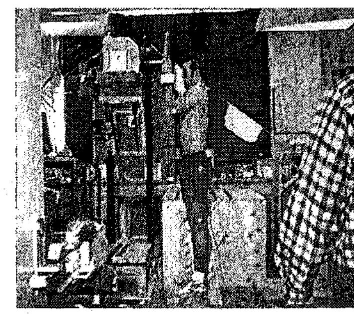
C. 90° Angle, Flat Surface,
58 cm Distance, 168 cm Height



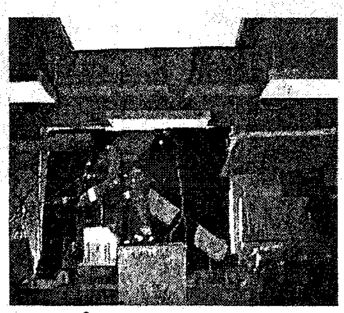
D. 90° Angle, Convex Surface,
19 cm Distance, 35 cm Height



E. 90° Angle, Convex Surface,
19 cm Distance, 93 cm Height



F. 90° Angle, Convex Surface,
19 cm Distance, 168 cm Height



G. 0° Angle, Flat Surface,
19 cm Distance, 35 cm Height

H. 0° Angle, Flat Surface,
19 cm Distance, 93 cm Height

I. 0° Angle, Flat Surface,
19 cm Distance, 168 cm Height

Figure 7.4: Example of experimental conditions.

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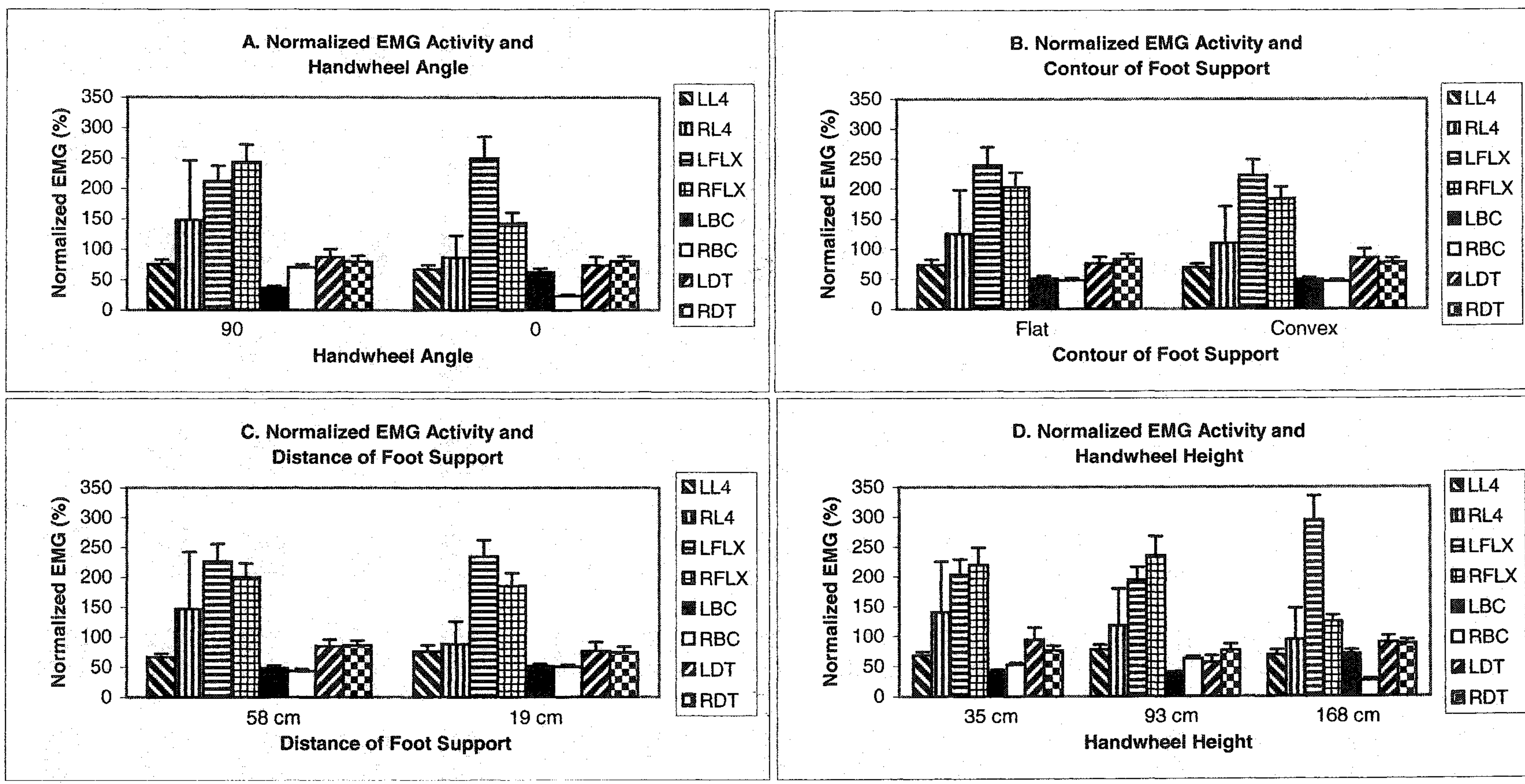

Figure 7.5: Normalized EMG activity for the four independent factors. Error bars indicate the standard deviation. A. Handwheel angle. B. Contour of foot support. C. Distance of foot support. D. Handwheel height. LBCP = Left Bicep; LDT = Left Deltoid; LFLX = Left Flexor Carpi Radialis; LL4 = Left Erector Spinae at the fourth Lumbar Vertebrae; RBCP = Right Bicep; RDT = Right Deltoid; RFLX = Right Flexor Carpi Radialis; RL4 = Right Erector Spinae at the fourth Lumbar Vertebrae.

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Chapter 8

Biomechanical Loads in the Low Back during Industrial Handwheel Actuation[1]

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8.1 Introduction

The current state of opinion regarding the issue of occupational injury to the low back is that the problem is multifactorial in nature and is mediated by personal, psychological and job related factors (Kumar, 2001; Marras, 2000; Keyserling, 2000a). Various degrees of association between these numerous factors and risk of injury have been reported. One factor that is supported by strong evidence is that of lifting and forceful movements, job tasks requiring workers to undertake such movements are associated with an increased risk of injury (Marras, 2000).

Based upon broadly defined occupation groups, work-related injuries and illnesses incurred by operators and laborers are associated with the highest claim costs (Leigh & Miller, 1997). Forceful movements are not uncommon to these occupations. One job task frequently undertaken by operators which has been reported to require extremely forceful movements is that of industrial handwheel actuation (Amell & Kumar, 2001; Parks & Schulze, 1998; Woldstad *et al.*, 1995; Johnson & Woldstad, 1993; Jackson *et al.*, 1992). This task requires large forces to be manually exerted upon a handwheel in order to generate a torque which in turn operates a valve or pressure system, or in some applications, brakes (Woldstad *et al.*, 1995). These systems are commonly found in heavy industries such as petroleum and chemical processing, power generation, waste treatment and transportation. Typically, a large static force must be exerted to 'crack' or 'break' the handwheel, followed by a much lower dynamic force to turn the wheel through its operational range. These large static forces are presumably associated with proportionately large biomechanical loads acting upon the low back and upper extremity.

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To further compound the issue, handwheels are rarely located in easy-to-access locations, i.e., they are frequently located at heights above the shoulder or below the knee, and are often situated in confined areas. Additionally, they are found in various pitch angle orientations such as 0^o, 45^o and 90^o to the horizontal. All of these design variables combine with the excessive force requirements to form a job task that has the potential to cause musculoskeletal injury.

It has been reported that over 55% of the low back injuries suffered by operators at a large petroleum company were associated with handwheel actuation (Parks & Schulze, 1998). In addition, 20% of upper back injuries and 75% of head, neck and face injuries reported by operators were also associated with handwheel actuation (Parks & Schulze, 1998). This reflects upon the hazardous nature of this job task.

In the only study of its kind reported in the literature, Johnson and Woldstad (1993) developed an optimization-based static three-dimensional model of the low back for use in calculating the compressive force during single-handed manual operation of a vertically orientated handwheel. The model calculated compressive forces acting upon the L3/L4 intervertebral disc that ranged from 4200 N to 6900 N in males and 1600 N to 2200 N in females. This study did not address two-handed handwheel actuation, handwheels of various pitch angles or the handwheel height above grade due to the fact that it was a targeted study of rail car breaking mechanisms, and single handed efforts were required.

Several tools exist for calculating the biomechanical loads acting upon the low back (Lavender *et al.*, 1999; Marklin & Wilzbacher, 1999; Waters *et al.*, 1998; Waters *et al.*, 1993; Chaffin & Andersson, 1991). The majority of these tools were developed for use in the analysis and design of manual materials handling job tasks. Due to the similarities between the job tasks of lifting/lowering, and pushing/pulling and that of handwheel actuation, these tools may be used in the analysis of this task, however such a study has not been reported in the literature. During two-handed handwheel actuation (counter-clockwise turning) in the vertical plane (90^o), the left hand ‘lowers’ or ‘pushes down’ upon the wheel while the right hand ‘lifts’ or ‘pushes up.’ Similarly, during actuation in the horizontal plane the left hand ‘pulls’ towards the body while the right

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hand 'pushes' away from the body. The combined effect of these movements results in a net tangential force about the handwheel in the counter-clockwise direction.

The majority of manual materials handling studies reported in the literature all address job tasks where the hands, as the point of external load application, move in the same direction, e.g., lifting a load to a height (symmetrical or asymmetrical) or pushing a load onto a shelf. The handwheel turning task involves simultaneous pushing/pulling or lifting/lowering, with the hands moving in opposite directions. Since no other study, with exception of the work of Johnson and Woldstad (1993) has investigated the biomechanical loads acting upon the musculoskeletal structures during handwheel actuation, this was viewed as a substantial gap in the knowledge base. Furthermore, it was also viewed as an opportunity to apply a widely used, existing static three-dimensional analysis tool to this hazardous job task.

The purpose of this study was to determine the biomechanical loads acting upon the low back during the development of maximal two-handed static handwheel cracking forces at different handwheel heights, orientations, distances and contours of foot support. Another purpose was the determination of the proportion of the population with sufficient strength (percent capable) to safely complete the job task. It was hypothesized that the biomechanical load as well as the population with sufficient strength would vary as a function of the independent variables selected for inclusion in the study. A final purpose was to demonstrate the ease of determining these biomechanical loads using the most commonly used analysis software available in the marketplace.

8.2 Methods

8.2.1 Participants

Twenty healthy males who reported no musculoskeletal injuries at the time of the experiment participated in the study. The study was approved by the University of Alberta Health Research Ethics Board. The participants were recruited from the general population of students at the University, and all provided informed consent. The participants were required to complete the PAR-Q questionnaire to assess their fitness for

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physical work (Shephard, 1988). All participants were compensated at a rate of $10 per hour. The mean age, weight and height of the sample was 24.2 ± 2.7 years, 75.5 ± 8.5 kg, and 178.8 ± 6.1 cm. Two of the participants were left hand dominant and none reported to be smokers.

8.2.2 Experimental Design

8.2.2.1 Independent Variables

A total of twenty-four experimental conditions were tested. The independent variables consisted of the following: 2 handwheel pitch angles (0° and 90° to the horizontal); 2 contours of foot support (flat and convex [standing upon a 28 cm diameter pipe]); 2 distances of foot support (19 cm and 58 cm); and 3 handwheel heights (35, 93 and 168 cm from the grade). Figure 8.1 is an example of the postures assumed during the task.

The two handwheel pitch angles represent two commonly found handwheel orientations in petroleum refineries. The two contours of foot support represent two possible surfaces that workers in the field are required to stand upon when actuating handwheels. Optimum contour of foot support is considered to be flat, while sub-optimum contour is considered to be convex, such as is found when a worker must stand upon a pipe or vessel in order to access a handwheel. The distances of foot support represent conditions whereby the worker must stand behind or lean over a pipe or obstruction or is forced into a confined space by another obstruction such as a pipe rack in order to access and actuate the handwheel. The support distances were determined by the following two equations: (0.75) X (50^{th} percentile male maximum reach), which yielded 58 cm; and (0.25) X (50^{th} percentile male reach), which yielded 19 cm (Chaffin & Andersson, 1991). The 3 different handwheel heights simulate conditions whereby the worker must access a handwheel at low or high heights relative to their stature. These values were determined by the following two equations: (50^{th} percentile male knee height) – (15 cm) which yielded 35 cm; and (50^{th} percentile male shoulder height) + (25

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cm) which yielded 168 cm. The 93 cm height is the hip height of the 50th percentile male (Chaffin & Andersson, 1991).

8.2.2.2 *Dependent Variables*

The dependant variable related to the external biomechanical load was the mean of three maximal-effort static physical exertions measured in Newtons of net tangential force during each experimental condition. The dependent variables analyzed included the low back compression, anterior/posterior and lateral shear forces at the L4/L5 lumbar level, the percent of population capable for the elbow, shoulder, torso, hip, knee, ankle as well as the estimated ligament strain on the L5/S1 lumbodorsal fascia. These loads were compared with the independent variables of pitch angle, contour of foot support, distance of foot support, and handwheel height.

8.2.2.3 *Task*

The participants were required to produce three maximal-effort static exertions at each experimental condition on a custom-built handwheel force measuring device in a random order of presentation (3 X 24 = 72 trials in total). Each exertion was 5 seconds in duration, and a minimum of 2 minutes rest was provided after each trial. The participants were required to gradually increase their effort for 2 seconds, after which they were to be at their maximum, and then were required to continue holding their maximum force for an additional 3 seconds. The highest net tangential force recorded in each was referred to as the maximum external load. The participants were permitted to grip the handwheel at any point on the circumference they desired, however they were not permitted to grip the handwheel spokes. They placed the center of their feet on one of two parallel lines on the flooring surface (19 and 58 cm). All exertions were counter-clockwise in direction in order to simulate the real-world handwheel cracking task. The participants were encouraged to familiarize themselves with each posture prior to the recorded trials. They were also encouraged to choose a posture that they believed would permit them to produce their maximum static net tangential force upon the handwheel. The participants

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were required to maintain the same posture for all three recorded trials for each condition, resting was permitted between exertions.

8.2.2.4 Participant Preparation

Five 2 cm diameter reflective markers were placed over the following joints on the left side of the body: ankle (lateral malleolus); knee (head of fibula); hip (greater trochanter); elbow (lateral epicondyle); and shoulder (acromion). In addition, reflective wrist bands were worn bilaterally and the medial epicondyle of the right elbow was marked. These markers were used to determine joint angles for use in the calculation of the internal biomechanical loads.

8.2.3 External Biomechanical Loads

The participants exerted upon a handwheel with a diameter of 42 cm (figure 8.1) and through a simple gear mechanism, an attempted rotation of the handwheel resulted in a linear tensile force being applied to a load cell (Omega Type S load cell, model LCCB-1K, Omega Engineering, Stamford, CT, USA).

8.2.4 Data Acquisition

The load cell output (external load) was acquired through an AD board model DT 2801-A (Data Translation, Marlboro, MA, USA) connected to an Intel Pentium class desktop computer. Sampling rate was set to 1000 Hz and custom-written data acquisition software was used to capture all data. The body posture was recorded on VHS videotape with the participants facing left for all experimental trials.

8.2.5 Internal Biomechanical Loads

The 3D Static Strength Prediction Program (3DSSPP™; Version 4.3; University of Michigan, Center for Ergonomics, 2001) software was used to calculate the internal

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biomechanical loads acting upon the musculoskeletal structures. This software requires the height, weight, and gender of each participant, as well as the external biomechanical load, information concerning the task to be analyzed (lifting, lowering, pushing, pulling), the direction the participant is facing, as well as the joint angles for each link segment.

The joint angles were determined via still digital image capture from the VHS videotape recording of each experimental trial. Still digital images were captured using an ATI All in Wonder Pro video card (ATI Technologies, Thornhill, Ontario, Canada) installed in a personal computer; all images were captured in bitmap format. The images were captured approximately 4 seconds into the 5 second trial. The images were then input into a custom-written angle resolution program capable of extracting the relevant joint angles after identifying the relevant joint markers. An output file listing all the relevant angles, external load, participant information, and task description was then created and input into the software in order to determine the internal biomechanical loads.

8.2.6 Software Setup

The software is capable of analyzing a wide variety of static occupational tasks, and yields a significant amount of useful information. After the angle output file from the customized angle determination program was input into the software, the appropriate hand load vectors were assigned. Different hand load vectors were necessary due to the fact that the pitch angle orientation of the handwheel significantly affected the nature of the task. In the vertical (90° to the horizontal) pitch angle orientation, under static counter-clockwise efforts, the left hand 'pulled down' ('pushed down') while the right hand 'pulled up' ('lifted'). Similarly, in the horizontal pitch angle orientation, the left hand 'pulled back' while the right hand 'pushed forward.' It was assumed that each hand contributed to 50% of the load. The end result of this force couple was the recorded net tangential handwheel force.

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8.2.7 Data Analysis

8.2.7.1 Reliability and Error

The mean of the three maximal-effort static exertions upon the handwheel, measured in net tangential force was input as the external load into the software. The reliability of the technique as well as the error associated with deriving static 3D data from a 2D video source was estimated using various measures of reliability (coefficient of variation, Pearson correlation, and intraclass correlation). The reliability of the angle resolution technique was assessed by replicating the digitization one participant's experimental trials using the angle resolution software. A participant was chosen at random and the images associated with each experimental trial were re-digitized and re-analyzed.

Although the task was predominantly symmetrical, the potential effect of error associated with deriving static 3D data from a 2D source was assessed. This was accomplished by one participant assuming the 'normal' posture that they believe would have permitted them to produce their maximum force, as during the actual experiment, as well as assuming a 'maximal induced error' posture whereby the participant rotated out of plane to the maximum amount permissible by the handwheel force measuring device. In the vertical pitch angle orientation this involved lateral flexion of the trunk towards the camera, as much as possible while maintaining grip and foot contact. In the horizontal pitch angle orientation this involved lateral translation of the pelvis under similar restraints. The mean external biomechanical load, height and weight of the 20 participants were input for each experimental condition as variables in the error estimates.

8.2.7.2 Body Posture

In order to maintain external validity, posture was left to the discretion of the participants. They were required to assume a posture that they believe would allow them to produce their maximum net tangential force. This resulted in two possible postures being adopted for the lowest handwheel height (35 cm) in both the vertical and horizontal

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pitch angle orientations. Participants either adopted a 'stoop' posture whereby the legs were predominantly straight and the trunk was flexed, or they adopted a 'squat' posture whereby the legs were flexed and there was little trunk flexion. If the participants assumed a posture at this handwheel height with a knee flexion angle less than 90^{o}, it was considered a 'squat.' All other experimental conditions at this height were deemed 'stoops'. An ANOVA was used to test the effect of posture against the peak net tangential force as well as the low back compression at the L4/L5 level.

8.2.8 Statistical Analysis

The calculated spinal compression and shear forces as well as the population strength were subject to repeated measures ANOVA. The statistic of choice was Pillai's test. All statistical tests were measured against the significance level of 0.05. The Statistical Package for the Social Sciences (SPSS Inc., Chicago, IL, USA) version 10.0.5 was used in all statistical analyses.

8.3 Results

8.3.1 External Biomechanical Loads

The mean net tangential forces developed by 20 participants (external biomechanical loads) which were input into the software are listed in table 8.1. In practice, the individual values (mean of three maximal effort trials) were input into the program. The individual external loads ranged from 220 N to 1360 N. The mean coefficient of variation amoung the net tangential forces for the three trials was 6.54%, while the minimum was 4.26% and the maximum was 9.59%. This indicates that the efforts may be considered maximal since these values all reside below 10%, the critical level for determining maximum effort reproducibility.

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8.3.2 Reliability and Error

With respect to the reliability of the angle resolution technique, the re-digitized angles resulted in minute differences between the original and re-analyzed trial. There was less than 1% difference (0.95%) between the calculated low back compression at the L4/L5 level between the two trials. The coefficient of variation was 0.67%, the Pearson correlation coefficient was 0.99, and the intraclass correlation coefficient was 0.99 between the trials, indicating very high reliability. With respect to the potential impact of deriving 3D data from a 2D source, the percent difference between the 'normal' and 'maximal induced error' trials was less than 6% (5.31%).

The coefficient of variation was 3.86%, the Pearson correlation coefficient was 0.78, and the intraclass correlation coefficient was 0.76, indicating no appreciable affect of 'maximal induced error' on spinal compression.

8.3.3 Body Posture

The contour of foot support did not alter the overall body posture significantly. The pitch angle did affect the wrist orientation; however it did not affect the overall body posture. The posture assumed, either 'stoop' or 'squat' for the lowest height (35 cm) conditions did not affect the net tangential handwheel force ($p = 0.392$) produced by the participants. However, the low back compression at the L4/L5 level was ($p = 0.011$). This difference is minor as the overall mean compression in those choosing to adopt the 'stoop' posture was 3371 N, while the mean compression in those adopting the 'squat' posture was 3198 N, a difference of 173 N.

The coefficient of variation among the low back compression calculated at the L4/L5 level over the three trials varied insignificantly as a result of the posture assumed by the participants over the three trials. The mean coefficient of variation was 3.44%, while the minimum was 1.86%, and the maximum was 8.50%. This indicates that posture was stable amoung the three experimental trials, and since maximal effort was assured by the low coefficient of variation exhibited amoung net tangential forces, confidence may

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be placed in these values. Posture in this sense refers to the joint angles of the three digitized experimental trials.

8.3.4 Internal Biomechanical Loads

The mean spinal compression and shear forces at L4/L5, as well as the percent ligament strain at L5/S1 are illustrated in figure 8.2. The low back compression values ranged from 2400 N to 3600 N for the mean of 20 participants; while the individual participant values ranged from 400 N to 5500 N.

The experimental conditions under which the compression was greatest was associated with a horizontal pitch angle, a convex foot contour, a support distance of 19 cm and a handwheel height of 35 cm. Compression was lowest with a horizontal pitch angle, a flat foot contour, a 19 cm support distance was and a height of 168 cm.

The main effects of the repeated measures ANOVA are listed in table 8.2. Based upon mean data, the vertical orientation induced higher low back compression than the horizontal orientation, although the mean difference was small, less than 100 N. Conversely, the effect of height was large, with the mean compressive force at the 35 cm height inducing almost 450 N more force than the other heights. This difference resulted in compression values at the 35 cm height exceeding the 3400 N Back Compression Design Limit.

Based upon interactions, significantly less shear force was observed in the vertical orientation and a distance of 58 cm. Lateral shear about the L4/L5 lumbar level followed the same pattern as anterior-posterior shear and was greater in the horizontal pitch angle ($p = < 0.001$), convex surface contour ($p = < 0.001$) and 19 cm distance ($p = < 0.001$). Anterior-posterior shear was greatest at the lowest height, followed by the middle and highest heights ($p = < 0.001$).

The ligament strain on the lumbodorsal fascia was significantly affected by height ($p = < 0.001$), being greatest in the lowest handwheel height (35 cm) and least at the highest handwheel height (168 cm). However, even the highest of these values is below the injury threshold of 30%.

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Table 8.3 lists the percentage of population capable of producing sufficient strength at each major joint. The elbow, shoulder and torso exhibited the lowest percentage of population capable score, regardless of condition. This indicates that these muscles are stressed significantly under these experimental conditions. Pitch angle, distance of foot support and height all affected the proportion of the population capable of generating sufficient muscle strength to produce the required forces (see table 8.2). The vertical angle orientation, 58 cm distance and the 35 cm handwheel height were associated with the lowest percent capable values for the elbow. Similar results were observed for the shoulder. Torso strength was also observed to be a factor in strength prediction and the predicted capabilities were lowest in the 168 cm height for this body area.

8.4 Discussion

The results of the experiment suggest that the dependent variables pertaining to static biomechanical loads acting upon the low back, as well as the population strength parameters were responsive to independent variable manipulation. In addition, the software was shown to be of great use in the analysis of the previously unstudied and commonly performed task of static, maximal effort two-handed handwheel actuation.

The minor but statistically significant effect of pitch angle orientation on the low back compression may be attributed to several factors. In the vertical plane, more net tangential force (external biomechanical load) was developed, and as a result, more load was borne by the low back. The reason for the greater force and accompanying load may be due to the functional anatomy of the upper extremity. In the handwheel actuation task, flexion of the forearm about the elbow in combination with anterior flexion of the arm about the shoulder (lifting) via action of the biceps brachii and anterior deltoid muscles produced the right-handed portion of the net tangential handwheel force. This force could have also been augmented somewhat by extension of the legs, plantar flexion of the feet or by a left-effort of the torso. The left-handed forces are derived from the triceps brachii, posterior deltoid and latissimus dorsi activity, which produce extension of the forearm at the elbow and the arm about the shoulder (pushing down). These motions may permit

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more force to be generated than the push-pull movements associated with the horizontal plane actuation. In this movement, the right hand pushes away from the body through the extension at the elbow and flexion at the shoulder while the left hand pulls towards the body through the flexion at the elbow and extension at the shoulder.

Due to mechanical advantage, elbow flexion strength is greater than extension strength (Chaffin & Andersson, 1991), and pulling strength is greater than pushing strength (Kumar, 1995). Since the majority of the participants were right hand dominant, one could surmise that in the vertical plane, where flexion of the right elbow was predominant, that more force was developed than in the horizontal plane, where the right elbow was relegated to pushing. Also, it is possible that small amounts of lateral torso flexion were present in the form of a left-effort in the vertical handwheel plane, as noted above. Support for this is derived from the fact that there was a 5% difference between the 'normal' and 'maximal induced error' postures. This left-effort in this plane could affect the force much more than the right-pelvic translation (lean) associated with the horizontal plane activities.

The end result of this increase in net tangential handwheel force production in the vertical plane is that more force is acting vertically, thus contributing to compression force in the low back. In the horizontal handwheel plane, push-pull forces dominate, which invariably results in more force acting transversely than vertically upon the low back, as evidenced by the higher shear forces and lower compression forces for this handwheel orientation (see figure 8.2).

While the effect of pitch angle on low back compression was comparatively small, the effect of height was large. This is attributable to two factors, torso flexion and external biomechanical load. In the lowest handwheel height, a significant amount of forward flexion of the torso about the hip was required in order to carry out the task. When this factor is combined with the large forces exerted upon the handwheel at this height, the large compression forces acting upon the low back are expected. These large forces coupled with a flexed spine are particularly hazardous to the operator as the spine is more susceptible to injury in this state (Marras, 2000; Gunning *et al.*, 2001; McGill, 1997). Interestingly, the highest handwheel height induced more biomechanical load than the middle height. The opposite would be expected because at the 93 cm height, some

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forward flexion of torso was still present, while at the 168 cm height, all participants were standing erect. This clearly indicates that the external biomechanical load does indeed play a significant role as this observation is attributed to the higher handwheel forces attained in higher handwheel height. These higher forces presumably offset the effect of neutral torso posture and may in fact lead to an overestimation of the actual compressive forces acting upon the region in this body posture.

The mean low back compression observed in this sample at the lowest handwheel height exceeded the generally accepted threshold that defines an increased risk of injury (Waters *et al.*, 1993). A compressive force of 3400 N is considered to represent the point at which micro-fractures begin to occur at the level of the vertebral end plate (Marras, 2000). As a result, a compression force of 3400 N is considered hazardous to some individuals, while a compression force of 6400 N is considered hazardous to most (Marras, 2000). Thus these maximum levels of exertion, combined with the body posture necessary to actuate the handwheel at such a low height are believed to be sufficient to cause injury to the low back in some individuals.

Although the shear forces were low, and presumably well below the injury threshold of between 750 and 1000 N (Marras, 2000; McGill, 1997) the observed results are compelling. Both lateral and anterior-posterior shear were much larger in the horizontal pitch angle orientation. The explanation of this observation is linked with the reasoning noted above for the low back compression. The maximal push/pull exertions necessitated by this pitch angle result in the majority of the force acting transversely. These predominantly transverse (horizontal) forces invariably manifest into shear force acting upon the low back about the anatomical planes in question (Garg, A, 1992). These forces arise as the spine flexes and accommodates to the desired neural input with the goal of a stable torso and a maximal physical muscular exertion, in this case the simultaneous pushing (right hand) and pulling (left hand) as the participants attempted to rotate a stationary handwheel in a counter-clockwise manor.

Since these biomechanical loads were calculated under artificial and experimental conditions, including strict control of foot placement, and the efforts were voluntarily elicited maximal exertions, they may not reflect the true levels of stress to which workers in the field would be exposed. The required handwheel cracking moments in the field

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have been reported to be as high as 400 Nm (Jackson *et al.*, 1992), even with a large handwheel such moments would require large net tangential forces. For example, to achieve a 400 Nm moment on the handwheel force measuring device used in this experiment, which had a radius 21 cm, the operator would have had to exert over 1900 N of net tangential force. In addition to forceful exertions and movements consisting of forward flexion of the spine, rotational movements (asymmetrical postures) may also be required in the field, which are also known to be injurious (Marras, 2000; Gunning *et al.*, 2001). Thus it is conceivable that in the absence of a handwheel actuation task designed within the capacity of the worker (force, height, orientation, footing etc.), that very large compressive and shear forces may be acting upon the low back when these handwheels are operated in-situ. The results revealed by this experiment underlie the importance of implementing ergonomically based engineering controls of handwheel-based mechanical systems.

Another issue of importance when interpreting the biomechanical loads derived from the analysis is that the computed values are for a single-incident maximal effort exertion. It has been reported by several authors that the spine has a memory and residual, cumulative effects of past loading history can weaken the spine and render it more susceptible to injury over time (Marras, 2000; Gunning *et al.*, 2001, Kumar, 1990). Compression and shear force tolerance limits vary with age and gender, in addition to past loading history. As a result, the effect of repetitive loading of the low back in the field through the actuation of many handwheels over the course of a work shift, week, month, year or career could accumulate to the point where injury is sustained with sub-maximal exertions. This notion is particularly applicable to industries which frequently rely upon handwheels to control process (petroleum, chemical), as they are typically dominated by older males who have worked as trades people for the majority of their adult years.

The results of the experiment indicate that the strength demands of the task, particularly with respect to the capacity of the upper extremity and torso, were high since well below 50% of the referent population are capable of producing such joint moments. Tasks involving the upper extremity and high force requirements are known to be injurious (Keyserling 2000b). Furthermore, it has been reported that torso position does

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not affect upper extremity adduction strength (Amell *et al.*, 2000), which is a key component in the stabilization of the shoulder during static efforts. Since the upper extremity strength is not affected, motions requiring awkward body postures may contribute to the high load imparted on musculoskeletal structures which cannot readily withstand higher loads in such postures, such as the low back (Amell *et al.*, 2000).

Since this is a novel application of an existing analysis tool, there is one limiting factor that warrants discussion. In order to obtain the biomechanical loads for this task, the software required that the magnitude and direction of the external load at the point of force application (the hands) be input. The static handwheel actuation task involved the simultaneous application of two forces, on opposite sides of the handwheel. These forces consisted of tangential forces to the handwheel, which are the sole contributors to the moment about the handwheel, as well as the non-tangential forces related to the grip (McMulkin & Woldstad, 1995). Since the forces are being applied to a circular object, the net effect of adding these two opposing tangential forces is an attempted rotation about the center of the circle, in this case, the handwheel hub, and it is this force that was measured by the load cell. It was assumed that each hand contributed to 50% of the external load, meaning that the forces, in a purely mechanical sense, essentially cancel one another out. This has the potential effect of overestimating the true loads being imparted upon the musculoskeletal tissues, particularly the low back. However, the software accepts opposing forces and directions at the hands (vectors), and hence adjusts for this effect and determines a value corrected for this factor. For example, in one experimental condition, the low back compression was 2366 N using the hand load vectors specific to the handwheel actuation task in the vertical pitch angle orientation. The hand load efforts were changed to simulate lifting, that is simultaneous actions of both handed efforts moving in the same direction. This resulted in a 30% increase in the calculated compression. Thus, the handwheel actuation task does not impart the same biomechanical load upon the low back as lifting would under the same conditions, nevertheless it does impart a load that may pose a risk of injury to some operators.

If it were possible assign a relative magnitude specific to each direction of motion for each hand, a more accurate calculation of the internal loads could be obtained. Although the software can accept such an input, the present experiment could not provide

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this information. Such information would be valuable to accurately determine if the participants were favoring one direction over another. The example of pushing upwards (lifting effort) with more force through the right hand, and less force pulling downwards (pushing down effort) at the higher handwheel heights in the vertical plane was alluded to earlier. This asymmetry could then be adjusted for in the analysis and more precise biomechanical loads could be computed to accommodate these efforts as it is known that asymmetrical movements are more injurious than symmetrical movements (Marras, 2000). Thus, the assumption of equal contribution to the effort by each hand would not be required. Nevertheless, the analysis of this previously unstudied task has proven to be of value, and the software demonstrated to be suitable at determining the risk of injury associated with this type of activity.

8.5 Conclusions

The outcome of the biomechanical analysis contained herein reveals that under experimental conditions of maximal effort two-handed static handwheel actuation, sufficient forces are generated in the low back that have the potential to cause injury. Furthermore, the task requires excessive amounts of upper extremity strength. The maximal strength capability and anthropometrics, particularly stature (height) of the operator must be considered when designing tasks that require the actuation of handwheels.

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Table 8.1: Mean external loads (net tangential handwheel forces). Standard deviations are in parenthesis.

Angle	Contour	Distance	Height	External Load (N)	Angle	Contour	Distance	Height	External Load (N)
90° (Vertical)	**Flat**	**58 cm**	**35 cm**	678 (167)	**0° (Horizontal)**	**Flat**	**58 cm**	**35 cm**	754 (168)
			93 cm	641 (137)				**93 cm**	679 (177)
			168 cm	760 (188)				**168 cm**	659 (122)
		19 cm	**35 cm**	753 (189)			**19 cm**	**35 cm**	621 (148)
			93 cm	628 (120)				**93 cm**	691 (185)
			168 cm	729 (181)				**168 cm**	585 (137)
	Convex	**58 cm**	**35 cm**	654 (159)		**Convex**	**58 cm**	**35 cm**	717 (141)
			93 cm	661 (136)				**93 cm**	719 (156)
			168 cm	754 (190)				**168 cm**	645 (145)
		19 cm	**35 cm**	692 (157)			**19 cm**	**35 cm**	640 (161)
			93 cm	640 (124)				**93 cm**	707 (160)
			168 cm	720 (171)				**168 cm**	631 (141)

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Table 8.2: Results of the repeated measures ANOVA. Checks indicate statistical significance at the α level of 0.05.

Main Effect	Angle	Contour	Distance	Height
Low Back Compressive Force at L4/L5	✔			✔
Anterior-Posterior Shear Force at L4/L5	✔	✔	✔	✔
Lateral Shear Force at L4/L5	✔	✔	✔	✔
Ligament Strain at L5/S1		✔	✔	✔
Elbow	✔	✔	✔	✔
Shoulder	✔		✔	✔
Torso	✔	✔	✔	✔
Hip	✔	✔	✔	✔
Knee	✔		✔	✔
Ankle	✔		✔	✔

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Table 8.3: Mean percent capable strength results. Standard deviations are in parenthesis.

Angle	Contour	Distance	Height	Elbow (%)	Shoulder (%)	Torso (%)	Hip (%)	Knee (%)	Ankle (%)
90° (Vertical)	**Flat**	**58 cm**	**35 cm**	3.3 (13.9)	16.7 (26.5)	46.4 (32.1)	83.0 (10.1)	54.2 (36.6)	51.1 (34.7)
			93 cm	2.8 (11.7)	7.2 (14.2)	80.7 (21.1)	93.3 (3.9)	83.5 (18.4)	39.1 (26.0)
			168 cm	12.2 (30.8)	0.1 (0.3)	78.7 (21.3)	95.5 (4.5)	80.9 (26.1)	41.3 (27.6)
		19 cm	**35 cm**	31.5 (40.3)	69.9 (36.1)	30.8 (30.0)	79.9 (10.9)	80.9 (31.8)	72.3 (24.6)
			93 cm	5.4 (15.0)	28.1 (25.8)	90.6 (12.2)	95.0 (4.8)	95.6 (13.1)	83.6 (18.5)
			168 cm	30.7 (38.0)	0.4 (1.6)	15.5 (21.9)	98.7 (0.8)	97.1 (6.0)	97.4 (2.9)
	Convex	**58 cm**	**35 cm**	0.7 (3.5)	24.6 (32.8)	47.6 (28.3)	82.4 (8.1)	65.1 (33.7)	56.2 (32.2)
			93 cm	0.3 (1.3)	7.2 (14.5)	85.3 (15.1)	93.9 (3.5)	84.7 (17.9)	35.1 (25.2)
			168 cm	3.6 (9.4)	2.3 (10.3)	81.4 (21.7)	95.6 (5.8)	84.3 (24.3)	54.9 (27.3)
		19 cm	**35 cm**	13.2 (28.7)	4.8 (19.6)	97.4 (2.2)	95.3 (1.6)	91.9 (5.5)	87.6 (11.5)
			93 cm	52.4 (42.3)	5.5 (14.4)	70.5 (22.1)	94.4 (2.2)	89.4 (17.8)	81.3 (9.4)
			168 cm	40.5 (41.8)	94.5 (15.6)	25.3 (27.4)	97.1 (0.9)	93.4 (16.2)	91.4 (4.4)
180° (Horizontal)	**Flat**	**58 cm**	**35 cm**	30.1 (44.4)	64.6 (38.0)	44.6 (33.2)	81.1 (10.7)	77.5 (38.3)	80.9 (17.3)
			93 cm	6.3 (20.8)	27.9 (26.9)	91.1 (13.2)	96.4 (3.0)	91.7 (22.2)	84.8 (15.2)
			168 cm	38.5 (39.3)	2.1 (9.3)	12.8 (20.0)	98.7 (0.9)	96.5 (4.0)	97.2 (4.7)
		19 cm	**35 cm**	44.5 (44.0)	0.5 (2.2)	95.8 (1.7)	87.2 (23.3)	95.1 (7.2)	97.9 (1.7)
			93 cm	10.2 (25.9)	3.2 (12.7)	42.9 (30.3)	96.7 (1.2)	98.7 (0.7)	97.4 (2.4)
			168 cm	36.7 (41.7)	93.6 (16.1)	18.4 (22.2)	98.3 (0.6)	98.9 (0.1)	98.3 (1.1)
	Convex	**58 cm**	**35 cm**	12.7 (29.3)	2.4 (10.0)	93.6 (11.2)	95.8 (1.2)	94.4 (8.0)	97.7 (1.4)
			93 cm	51.9 (41.6)	3.5 (10.3)	44.6 (33.5)	96.4 (1.1)	96.5 (8.4)	96.7 (2.6)
			168 cm	46.9 (42.1)	92.2 (20.7)	16.1 (24.3)	97.9 (0.9)	97.1 (8.7)	96.1 (9.2)
		19 cm	**35 cm**	11.9 (28.9)	0.4 (1.9)	95.4 (4.8)	94.8 (1.9)	91.1 (6.7)	86.8 (11.9)
			93 cm	52.8 (40.7)	6.8 (16.5)	59.5 (29.4)	95.7 (1.9)	92.7 (18.3)	89.8 (15.8)
			168 cm	44.5 (42.4)	96.5 (5.8)	18.8 (22.5)	97.1 (1.1)	86.5 (26.5)	87.3 (12.3)

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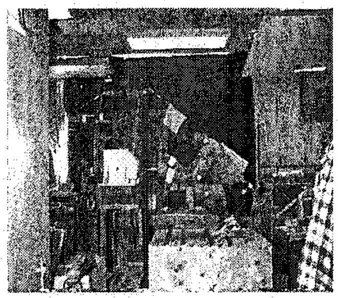
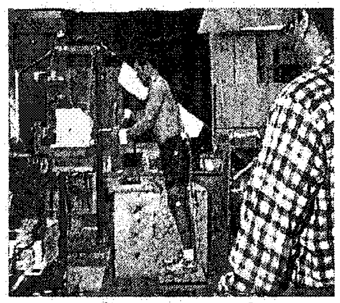
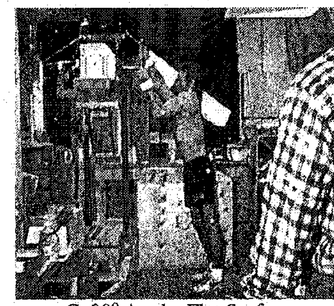


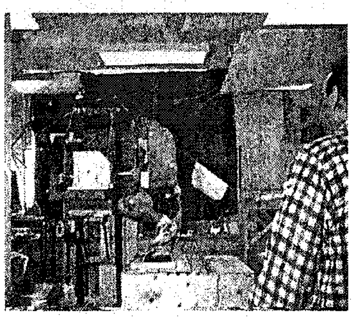
A. 90° Angle, Flat Surface, 58 cm Distance, 35 cm Height



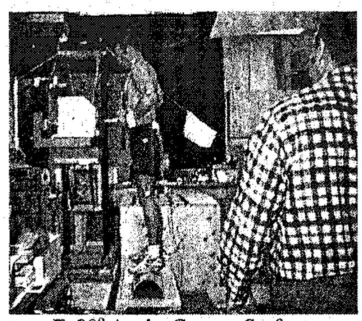
B. 90° Angle, Flat Surface, 58 cm Distance, 93 cm Height



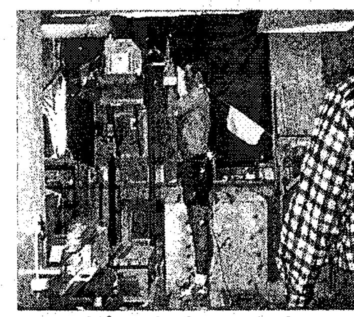
C. 90° Angle, Flat Surface, 58 cm Distance, 168 cm Height



D. 90° Angle, Convex Surface, 19 cm Distance, 35 cm Height



E. 90° Angle, Convex Surface, 19 cm Distance, 93 cm Height



F. 90° Angle, Convex Surface, 19 cm Distance, 168 cm Height

G. 0° Angle, Flat Surface, 19 cm Distance, 35 cm Height

H. 0° Angle, Flat Surface, 19 cm Distance, 93 cm Height

I. 0° Angle, Flat Surface, 19 cm Distance, 168 cm Height

Figure 8.1: Example of the handwheel actuation tasks examined.

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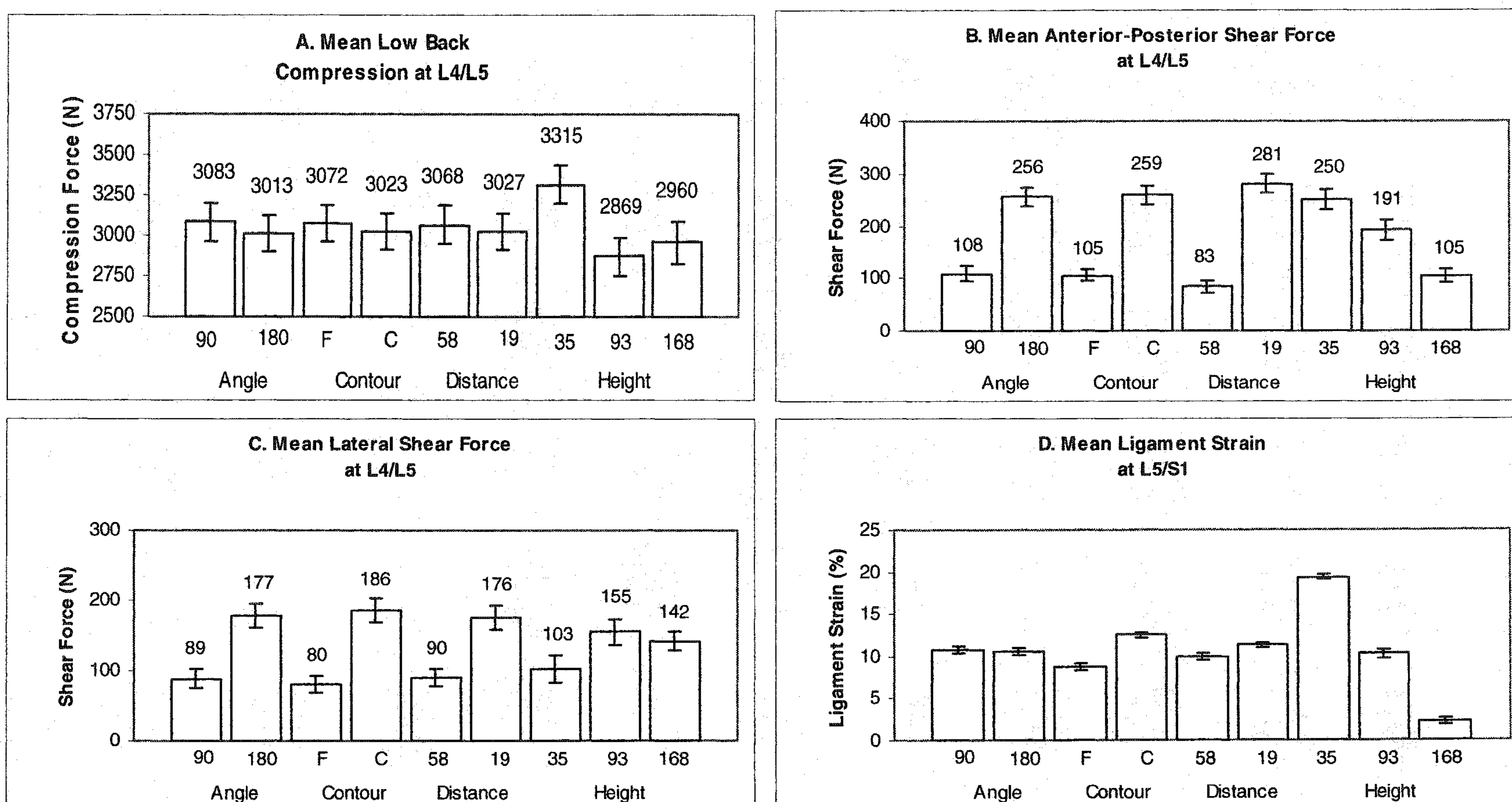

Figure 8.2: A. Low back compression force at L4/L5. B. Anterior-posterior shear force at L4/L5. C. Lateral shear force at L4/L5. D. Ligament strain at L5/S1. F = flat, C = convex, distances and heights are measured in cm.

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Chapter 9

Psychophysical and Physiological Loads during Industrial Handwheel Operation[1]

[1] This chapter has been submitted for publication in *Applied Ergonomics*. It is currently in the peer review process. AMELL, T., KUMAR, S. & NARAYAN, Y. Psychophysical and Physiological Loads during Industrial Handwheel Operation.

9.1 Introduction

Numerous risk factors for the development of musculoskeletal disorders have been reported in the scientific literature (Keyserling, 2000a and 2000b). Occupational tasks requiring forceful movements, high repetition and awkward body postures are associated with an increased risk of injury to the musculoskeletal system (Putz-Anderson, 1988). Typically, evidence for this association has been derived from studies based upon one, or a combination of two or more, of the following three approaches; biomechanical, psychophysical or physiologically based experiments (Waters *et al.*, 1993). All three of these approaches have yielded helpful results for use in efforts to control musculoskeletal disorders in the workplace.

One occupational task that is commonly associated with forceful movements, high repetition and awkward body postures is that of industrial handwheel operation (Amell and Kumar, 2001; Woldstad *et al.*, 1995; Jackson *et al.*, 1992). High rates of overexertion injuries in the population of workers responsible for handwheel operation have been reported (Amell and Kumar, 2001; Parks and Schulze, 1998). In handwheel actuation (commonly referred to as 'cracking'), an initial large net tangential force is required to initiate movement of the valve, breaking mechanism, or whatever process or system the handwheel control device is intended to regulate. The actuation of this 'cracking' force is typically quite large, is static (requiring isometric muscular exertion) and is followed by a substantially lower force once the handwheel has begun to move about its axis. Repetitive rotation of the handwheel then ensues throughout the operational range of the handwheel system, this action is termed handwheel operation.

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Although frequently used in the control of production processes in numerous heavy industries, including the petroleum and chemical industries, waste treatment, power generation as well as transportation, information on worker capabilities in relation to this important task is sparse (Amell and Kumar, 2001). Only a handful of studies of this task have been reported in the literature, and of those, the majority have been purely biomechanical in nature and have been limited to the static component of this activity (Jackson *et al.*, 1992; Parks and Schulze, 1998; Woldstad *et al.*, 1995; Woldstad *et al.*, 1992; McMulkin *et al.*, 1995; McMulkin *et al.*, 1993; Johnson and Woldstad, 1993; Shih *et al.*, 1997; Shih and Wang, 1997). The dynamic component of handwheel operation has also been examined, again from a biomechanical perspective and in a limited capacity using isokinetic dynamometry (Schulze *et al.*, 1997a; Wood *et al.*, 1999/2000). Similarly, both static and dynamic operation of a wheel activated by a hand crank has been examined (Schulze *et al.*, 1997b; Raouf *et al.*, 1986; Raouf *et al.*, 1984). Additionally, applied studies of dynamic torque generating tasks common to the petroleum industry have been undertaken (Imrhan and Farahmand, 1999). No studies found in the literature have addressed the psychophysically based perceived exertion levels or the physiologically based response of the cardio-respiratory system to handwheel operation.

Psychophysics describes the response that organisms exhibit in reaction to environmental stimuli (Keyserling 2000a; Kumar *et al.*, 1999; Stevens, 1960). Pandolf *et al.* (1984) reports that it was Borg who first noted that the overall perception of effort during physical work represented the integration of various physiological sensations. The mechanisms underlying the relationship between physical work and the various physiological sensations of physical work as measured by the psychophysical test are believed to arise from feelings of strain in the contracting musclulo-tendinous units, joints, and the cardio-respiratory system (Garcin *et al.*, 1998).

The psychophysical technique has been shown to produce reliable and valid results in the evaluation of work tasks (Chan, 2000; Kumar and Simmonds, 1994; Gamberale, 1988). They have been used as a reliable indicator of tasks with high cardio-vascular demands (Hui *et al.*, 2001) as well as those associated with the development of musculoskeletal disorders (Kumar *et al.*, 2000; Kumar *et al.*, 1999; Kumar and Lechelt, 1999; Josephson *et al.*, 1996). In the study of physical work, many methods have been

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used to measure exertion and fatigue at the perceptual level. One commonly used measure is the rated perceived exertion (RPE), which is based upon subjective ratings of the corresponding perceived exertion during work. Using this measure, the Borg scale has been utilized to estimate how the individual perceives the intensity of work (ACSM, 1993). This scale, or similar rating scales, have been shown to relate closely to the heart rate, absolute oxygen consumption, relative aerobic demand, and levels of blood lactate of the worker (Garcin *et al.*, 1998; Gamberale, 1985).

Aside from the indirect measures of physiological performance (psychophysics) discussed above, there exists another class of direct means of assessing physiological load (Kumar *et al.*, 2000; Kumar *et al.*, 1999; Åstrand and Rodahl, 1977). These include the direct measurement of physiological variables such as heart rate and oxygen consumption during physical work via the use of telemetry-based or portable non-invasive equipment. Such equipment has been shown both reliable and valid (Harrison *et al.*, 1982). As work load increases, so does heart rate and oxygen consumption.

As noted above, the outcomes of the psychophysical tests are related to the underlying physiological experience and hence serve as measures of the loads acting upon the worker while occupational tasks are being performed. Since industrial handwheel operation has not been studied using these tools in the past, the present experiments were carried out in order to determine the capability of workers as well as the impact of various design and environmental factors thought to affect their capabilities during the completion of this important occupational task.

The purpose of the studies reported herein was to determine both the psychophysical and physiological loads experienced by workers during simulated industrial handwheel operation. It was hypothesized that the variables of handwheel height and pitch angle, as well as the distance and contour of foot support would affect the levels of perceived exertion during static handwheel actuation ('cracking'). In addition, it was hypothesized that the level of perceived exertion, heart rate and oxygen consumption during dynamic handwheel operation would vary with differing handwheel heights and distances of foot support.

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9.2 Methods

9.2.1 Participants

Twenty healthy male participants with no musculoskeletal injuries or cardio-respiratory conditions at the time of the experiment participated in the studies. The studies were approved by the University Health Research Ethics Board. The participants were recruited from the general population of students at the University, and all provided informed consent. The participants were required to complete the PAR-Q questionnaire to assess their fitness for physical work (Sheppard, 1988). All participants were compensated at a rate of $10 per hour. The mean age, weight and height of the sample was 24.2 ± 2.7 years, 75.5 ± 8.5 kg, and 178.8 ± 6.1 cm. Two of the participants were left hand dominant and none reported to be smokers.

9.2.2 Description of Experiments

Two experiments were conducted. Experiment 1 involved maximal effort static handwheel actuation under 24 experimental conditions. Psychophysical measures of perceived exertion and body part discomfort during the work activity were studied. Experiment 2 involved dynamic handwheel operation at a constant work load under 6 experimental conditions and was evaluated using both psychophysical as well as physiological measures of work performance.

9.2.3 Experiment 1

9.2.3.1 Design and Task

The participants were required to produce three maximal-effort static two-handed exertions at each experimental condition on a custom-built handwheel force measuring device (figure 9.1) in a random order of presentation (3 X 24 = 72 trials in total). This movement simulated the real-world task of industrial handwheel actuation ('cracking'),

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all exertions were counter-clockwise in direction. The circumference of the handwheel was 42 cm, an attempted rotation when the handwheel was locked in the static position resulted in a linear tensile load being applied to a load cell through a simple gear mechanism. Each exertion was 5 seconds in duration, and a minimum of 2 minutes rest was provided after each trial. The participants were required to gradually increase their effort for 2 seconds, after which they were to be at their maximum, and then were required to continue holding their maximum force for an additional 3 seconds. The participants were permitted to grip the handwheel at any point on the circumference they desired, however they were not permitted to grip the handwheel spokes. They placed the center of their feet on one of two parallel lines on the flooring surface. The participants were encouraged to familiarize themselves with each posture prior to the recorded trials. They were also encouraged to choose a posture that they believed would permit them to produce their maximum static net tangential force upon the handwheel. The participants were required to maintain the same posture for all three recorded trials for each condition. After each set of three experimental trials, the participants completed three psychophysical questionnaires while the investigators prepared the next condition.

Prior to the experiment, the participants were instructed on the proper procedures for completing the questionnaires. At this time the initial values were confirmed to be zero on the body part discomfort scale, indicating no musculoskeletal discomfort prior to the start of the experiment.

9.2.3.2 Independent Variables

The participants completed the above mentioned task under twenty-four experimental conditions with respect to various handwheel angles and heights as well as distances and contours of foot support. Distances were measured from the handwheel rim. The independent variables consisted of the following: 2 handwheel pitch angles (0^{o} and 90^{o} to the horizontal); 2 contours of foot support (flat and convex [standing upon a 28 cm diameter pipe]); 2 distances of foot support (19 cm and 58 cm); and 3 handwheel heights (35, 93 and 168 cm from the grade). Figure 9.1 depicts a participant during one of the experimental trials.

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The two handwheel pitch angles represent two commonly found handwheel orientations in petroleum refineries. The two contours of foot support represent two possible surfaces that workers in the field are required to stand upon when actuating handwheels. Optimum contour of foot support is considered to be flat, while sub-optimum contour is considered to be convex, such as is found when a worker must stand upon a pipe or vessel in order to access a handwheel. The distances of foot support represent conditions whereby the worker must stand behind or lean over a pipe or obstruction or is forced into a confined space by another obstruction such as a pipe rack in order to access and actuate the handwheel. The support distances were determined by the following two equations: (0.75) X (50^{th} percentile male maximum reach), which yielded 58 cm; and (0.25) X (50^{th} percentile male reach), which yielded 19 cm (Chaffin and Andersson, 1991). The 3 different handwheel heights simulate conditions whereby the worker must access a handwheel at low or high heights relative to their stature. These values were determined by the following two equations: (50^{th} percentile male knee height) – (15 cm) which yielded 35 cm; and (50^{th} percentile male shoulder height) + (25 cm) which yielded 168 cm. The 93 cm height is the hip height of the 50^{th} percentile male (Chaffin and Andersson, 1991).

9.2.3.3 Dependent Variables and Equipment

The outcomes of three psychophysical questionnaires were the dependent variables in experiment 1. The questionnaires used were the Borg Rating of Perceived Exertion Scale (RPE), the Visual Analog Scale (VAS), and the Body Part Discomfort Rating (BPDR). Please refer to Kumar *et al.* (1999) for more information on these measures. The RPE is an interval scale ranging from 6 to 20 whereby the respondent circles a number corresponding to their level of perceived exertion, based upon the descriptors (Borg 1962). The VAS consists of a 10 cm horizontal line with the descriptors 'most comfortable' and 'most uncomfortable' at the ends of the line whereby the respondents mark their level of comfort along the continuum. The BPDR consists of a graphical depiction of a human figure divided into 'left' and 'right' body parts whereby the respondents indicate their level of perceived discomfort on a scale ranging from 1 to

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10 (Corlett and Bishop, 1976). The outcome of these questionnaires was compared with the independent variables of pitch angle, contour of foot support, distance of foot support, and handwheel height.

9.2.4 Experiment 2

9.2.4.1 Design and Task

Six experimental conditions were studied in experiment 2. Participants turned the handwheel in the counterclockwise direction using two hands with a constant force output (20 N) and at a constant rate (20 rpm) in 5 minute intervals at different distances of foot support and handwheel heights. The 20 N of force provided sufficient resistance to necessitate two-handed operation of the handwheel (i.e., it did not freely rotate) without imposing excessive force demands. This level of force was chosen due to the fact that handwheels rarely require large forces to rotate after they have been 'cracked' if the stem is sufficiently lubricated.

The same custom built handwheel equipment described in experiment 1 was used in experiment 2. Rather than being locked in a static position to simulate handwheel 'cracking,' as was required in experiment 1, during experiment 2 the handwheel was permitted to rotate, which simulated handwheel opening. The 20 volunteers who participated in experiment 1 were randomly assigned to one of two groups in experiment 2. There were 10 participants per group, with both groups completing the experiment at all three heights and one of the two distances of foot support. The presentation of the experimental conditions was randomized. As with the grip location restriction noted in experiment 1, the participants were limited to gripping the handwheel at the circumference and could not grip the spokes.

Prior to the onset of the experiment, oxygen consumption and heart rate monitoring equipment was fitted to the participants (figure 9.2). This equipment remained in place throughout the duration of experiment 2. The participants then rested in a seated position for 5 minutes in order to obtain baseline values. A buzzer sounded the end of the rest period, as well as all subsequent work and rest periods occurring thereafter. The

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participants then executed the first dynamic handwheel turning task for 5 minutes (figure 9.3), and then rested again. This was repeated for all 3 heights, each work period was separated by a 5 minute rest period. Including 3 dynamic work tasks and 4 rest periods, the total experiment lasted exactly 35 minutes.

After each work period, the participants returned to their seated position and completed the same ratings of perceived exertion and body part discomfort as they had done in experiment 1 while the investigators prepared the next condition. Experiment 2 took place at least 24 hours after experiment 1.

9.2.4.2 Independent Variables

The participants completed the study at one of two different distances of foot support (19 cm and 58 cm) and at each of the 3 handwheel heights (35, 93 and 168 cm). The 90° pitch angle orientation and flat surface contour was used in this experiment and these variables were not manipulated.

9.2.4.3 Dependent Variables and Equipment

The same three psychophysical questionnaires used in experiment 1 were dependent variables in experiment 2. In addition, two physiological measures of work performance were employed in order to measure heart rate and oxygen consumption, which were the remaining dependent variables in experiment 2. Heart rate was recorded using the telemetry-based Polar Vantage XL (Polar CIC Inc., Port Washington, NY, USA). This unit consisted of a recording device worn on the chest of the participant and a receiving unit located close to the recording device (figure 9.2). Heart rate values were measured every 5 seconds. The Morgan Oxylog2 (Morgan Medical Ltd., Kent, England) recorded such variables as ventilation ($l \bullet min^{-1}$) and VO_2 ($l \bullet min^{-1}$). This unit consists of a face mask worn by the participants (see figure 9.2), a turbine flow meter, an expired air hose and a light-weight analysis unit, worn upon a belt around the waist. Oxygen consumption data were measured every minute. The accompanying software and PC computer interfaces for each device were used to capture and analyze the data after each

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experimental session. The equipment was properly calibrated and sterilized prior to the experiment. The outcome of these measures was compared with the independent variables of distance of foot support, and handwheel height.

9.2.5 Analysis

The RPE and VAS data from both experiments were subjected to an analysis of variance (ANOVA). A repeated measures ANOVA was used in the static experiment while a univariate ANOVA was used in the dynamic experiment. *Post hoc* tests by the Scheffé method were computed to assess the directionality of the main effects in the dynamic experiment. The mean values for the static experiment were tested to assess the effect of handwheel pitch angle, contour of foot support, distance of foot support and height of handwheel on RPE and VAS score. The mean values for the dynamic experiment were tested to assess the effect of distance of foot support and height of handwheel on these same variables. The BPDR data were analyzed based upon frequencies and repeated measures ANOVA.

With respect to the physiological measures in the dynamic experiment, mean, minimum and maximum values for heart rate (HR) and oxygen consumption (O_2) during each 5 minute work and rest period were submitted to an ANOVA. The heart rate ($bt \bullet min^{-1}$) and oxygen consumption ($l \bullet min^{-1}$) were tested to determine the effects of distance of foot support and handwheel height. The Statistical Package for the Social Sciences (SPSS, version 10.0.5) was used for all computational procedures and all tests were measured against the 0.05 α level of significance.

In the essence of attempting to accurately simulate handwheel actuation and operation, as few restrictions as possible were placed upon the participants, with the noted exception of grip placement and distance of foot support. Since posture was left to the discretion of the participants, and they assumed a posture that they believed would allow them to produce their maximum net tangential force in experiment 1, this resulted in two possible postures being adopted for the lowest handwheel height (35 cm) in both the 90° and 0° pitch angle orientations. Participants either adopted a 'stoop' posture whereby the legs were predominantly straight and the trunk was flexed, or they adopted a

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'squat' posture whereby the legs were flexed and there was little trunk flexion. In experiment 1, if the participants assumed a posture in the 35 cm height condition with a knee flexion angle less than 90° it was considered a 'squat.' All other experimental conditions at this height were deemed 'stoops'. Similarly in experiment 2, the participants could have adopted either posture at the lowest handwheel height, regardless of the distance of foot support (figure 9.3). An ANOVA was used in order to test the effect of posture against the psychophysical and physiological variables examined.

9.3 Results

The effects of posture, that is, stoop versus squat positions in the lowest handwheel height for both experiments 1 and 2 were not statistically significant. Nine participants chose to adopt the squat posture for at least one of the twenty-four experimental conditions in the static experiment, neither the RPE ($p = 0.664$) nor the VAS ($p = 0.139$) were affected by this posture. Three participants chose to adopt the position in the dynamic experiment, and it did not affect the heart rate ($p = 0.414$), the oxygen consumption ($p = 0.632$), nor the dynamic psychophysical variables ($p = 0.224$).

9.3.1 Experiment 1

9.3.1.1 RPE and VAS

Figure 9.4 A-B illustrates the mean effects of the four independent variables upon the RPE and VAS scores for the static experiment. Based upon the outcome of the repeated measures ANOVA, the main effect of handwheel height was statistically significant ($p < 0.001$), and the 93 cm height was associated with the least RPE while the 35 and 168 cm heights were observed to produce similar levels of exertion. The effects of handwheel pitch angle ($p < 0.976$), contour of foot support ($p < 0.425$) and distance of foot support ($p < 0.758$) did not affect the RPE. A slightly different outcome was observed based upon the repeated measures ANOVA on the VAS scores. The contour of foot support significantly affected the VAS score, the flat contour was observed to be

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more comfortable than the curved contour ($p < 0.018$). The 93 cm handwheel height was also observed to be more comfortable than the other two heights ($p < 0.001$).

9.3.1.2 BPDR

The lower back and upper extremities were the most frequently reported body regions affected by perceived discomfort, based upon the BPDR. Repeated measures ANOVA revealed that only perceived discomfort in the lower back ($p < 0.041$) and left lower arm ($p < 0.042$) were significantly affected by handwheel height. The 93 cm height induced less discomfort in the lower back as well as the left lower arm than either the 35 cm or 168 cm heights. No other mean differences amoung body parts and the effects of angle, contour of foot support and distance from the handwheel were observed to be statistically significant.

9.3.2 Experiment 2

9.3.2.1 RPE and VAS

Figure 9.4 C-D illustrates the mean effects of the two independent variables upon the RPE and VAS scores for the dynamic experiment. The outcome of the repeated measures ANOVA revealed that the effect of handwheel height was statistically significant ($p < 0.001$) while the effect of the distance of support was not for both the RPE and VAS. *Post hoc* tests by the Scheffé method revealed that the 93 cm height engendered the least level of perceived exertion and was more comfortable than either the 35 cm height ($p < 0.001$) or the 168 cm height ($p < 0.002$). There was no significant difference between the RPE for the dynamic handwheel actuation task at the 35 or 168 cm heights. Similar results were observed for the VAS scores.

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9.3.2.2 BPDR

The lower back and upper extremity were the most frequently reported body regions affected by perceived discomfort, based upon the BPDR. No statistically significant mean differences among body part discomfort rating and the effects of distance of foot support and handwheel height were observed.

9.3.2.3 Heart Rate and Oxygen Consumption

Figure 9.5 is an example of the heart rate and oxygen consumption observed for one 35-minute experimental trial. Figure 9.6 A-B depicts the average, minimum and maximum values (bt•min^{-1}) for heart rate during a five minute period of continuous work at a constant rotation and force output. Bradycardia was present, albeit briefly, in two participants during the initial resting period. The work trials were associated with a significantly ($p < 0.001$) greater average heart rate. The average heart rate during the work trials was typically between 120 and 140 bt•min^{-1} with some individual participants' heart rate reaching 170 bt•min^{-1}. There was no difference between the mean heart rate with respect to distance of foot support or handwheel height, thus indicating that there was no appreciable effect of the variables tested on cardiac load.

Figure 9.6 C-D depicts the average, minimum and maximum values for oxygen consumption (l•min^{-1}) during the five minute period of continuous work at a constant rate and force output. The oxygen consumption mean values ranged from 1.2 to 1.4 l•min^{-1} (6 to 7 Kcal•min^{-1}), with individual values reaching as high as 2.2 l•min^{-1} (11 Kcal•min^{-1}). All experimental trials were associated with greater levels of oxygen consumption (average, minimum and maximum) when compared to the resting condition ($p < 0.001$). However, no differences were noted between the distance of foot support or the handwheel height.

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9.4 Discussion

The results indicate that the RPE and VAS varied as a function of handwheel height above the grade during maximal effort static handwheel actuation. When the handwheel was located at a height of 93 cm above the grade the body posture was neutral. Very little flexion of the trunk was required by the participants as compared to the 35 cm handwheel height. In addition, the task was in easy reach.

In contrast, some hyperextension of the trunk was required at the highest handwheel height. This handwheel height required that the upper extremities be flexed to a level in which the hands and forearms were located at positions significantly higher than the shoulder. Such an upper extremity posture is associated with an increased level of postural discomfort and injury, and an accompanying decrease in strength (Amell *et al.*, 2000; Hagberg *et al.*, 1995). In this position, the shoulder muscles must counter the force of gravity in order to stabilize the joint and permit the hands to function. Since more force must be devoted to the maintenance of posture, less force may be devoted to the required occupational task. Such a position could have been perceived to require more exertion, even if there was less force required for the task. Since the perceived exertion arises from biofeedback mechanisms in the contracting musculo-tendinous units and joints (Garcin *et al.*, 1998), and these postures required positions in which the muscles and joints were forced to counter large loads in an awkward posture, it would be expected that they induce higher levels of perceived exertion. This explanation holds true for the amount of trunk flexion at the 35 cm handwheel height as well, regardless of variation in squat or stoop posture.

The VAS score as a function of contour of foot support is interesting. The convex foot support could have required greater whole body effort in order to maintain balance on the curved surface versus the flat surface. Such a surface would have required that the center of mass of the body be continually shifted in an effort to maintain its location above the curved base of support, as a result an unbalanced position could have easily been attained and hence contributed to an increase in the level of perceived exertion. Since the RPE measures the physiological loading which remained unaffected by the contour of the foot support, it did not parallel the VAS observation.

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The left lower arm was associated with significantly higher frequency of reported discomfort. This could be attributed the observation that the majority of the participants were right hand dominant and may not have had adequate strength in the left upper extremity. Since maximal efforts were required in the static experiment, perhaps the lack of strength induced a level of overexertion and this manifested into the observation of greater discomfort in this body region.

With respect to the psychophysical results of the dynamic experiment, the same explanations hold true for the handwheel height differences and lack of difference between distances of foot support. There was, however, a more pronounced difference between the mean values at the 35, 93 and 168 cm heights in the dynamic experimental conditions. In the dynamic study, the participants were required to rotate the handwheel for 5 minutes, thus causing more physical work requirements during the 5 second trials in the static experiment.

No statistically significant differences due to height or distance were observed in the heart rate during the dynamic trials. The mean heart rates (figure 9.6) ranged from classifications of 'heavy work' to 'extremely heavy work' according to the physiological guidelines suggested by Åstrand and Rodahl (1977). The handwheel operation simulation trials exhibited working heart rates similar to those reported in field studies of other occupations (Kirk and Sullman, 2001). Thus, this task involves a significant cardio-vascular load on the operator. The observed oxygen consumption values during the work trials (figure 9.6) were also representative of 'heavy' to 'extremely heavy work' (Åstrand and Rodahl, 1977). In addition, the observed values during handwheel operation exceeded the upper limit of 4.7 kcal•min^{-1} for energy expenditure supported by the NIOSH group in the United States in their recommendations (Waters *et al.*, 1993).

Since young healthy males participated in this study, it can be safely stated that regardless of the cardio-respiratory fitness of the operator, the task of industrial handwheel operation involves a significant physiological load on the operator. These loads may contribute to both localized and generalized fatigue (Waters *et al.*, 1993). This may in turn manifest into an overexertion injury, or may contribute to other unrelated injuries due to fatigue and incoordination.

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There are several limitations in the studies. Firstly, hand gloves were not worn by the participants, which is contrary to what one would expect to encounter in the field. As a result, this may have artificially inflated the level of perceived exertion since presumably hand gloves serve to attenuate the kinesthetic awareness and increase the level of frictional forces at the hand. Without gloves, participants may have reported higher levels of perceived exertion since the forces were being perceived directly through the hands. However, since gloves increase the levels of exerted force, the effect of this remains unknown. Secondly, the experiment was conducted in a laboratory at a constant temperature which may not be encountered in the field. Finally, it could be argued that the physiological measuring equipment, most notably the Morgan Oxylog2 contributed to the physiological load on the cardio-respiratory system since the participant had to support the weight of this device. A recent study has rejected this hypothesis (Bales *et al.*, 2001), and furthermore the Oxylog2 weighs significantly less than the previous versions of this device.

9.5 Summary and Conclusions

The results of this experiment suggest that the design and environment of handwheel-based control device systems has an impact on both the subjective and objective physiological load experienced by the operator. As a direct result, the physiological capabilities of the operators are adversely affected by handwheel designs that force the assumption awkward body postures and require excessive muscular force.

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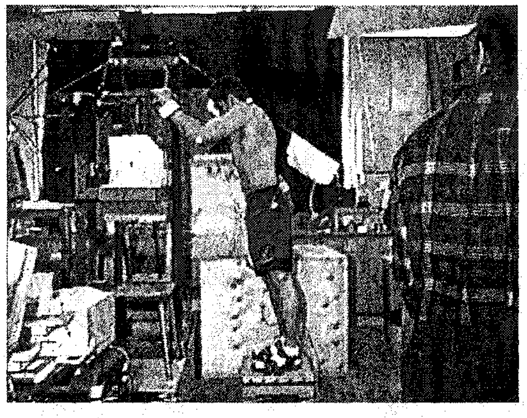

Figure 9.1: Example of a participant performing the static handwheel actuation task in experiment 1, simulated handwheel actuation with a 0° angle, flat surface, 58 cm distance, and 168 cm height.

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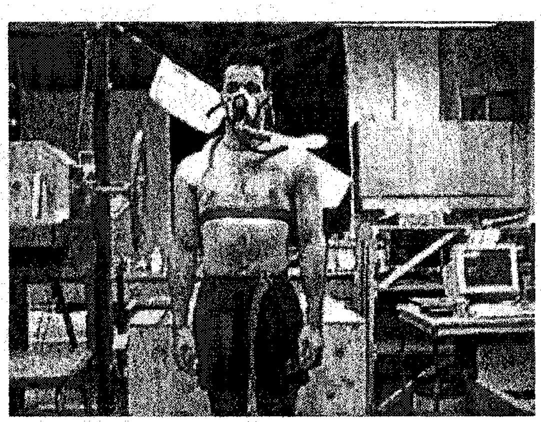

Figure 9.2: A participant fitted with the oxygen consumption and heart rate monitoring equipment in experiment 2.

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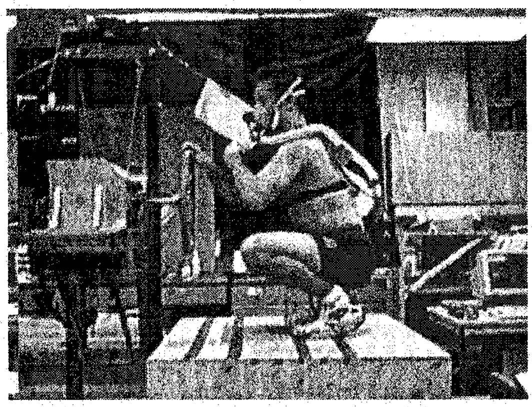
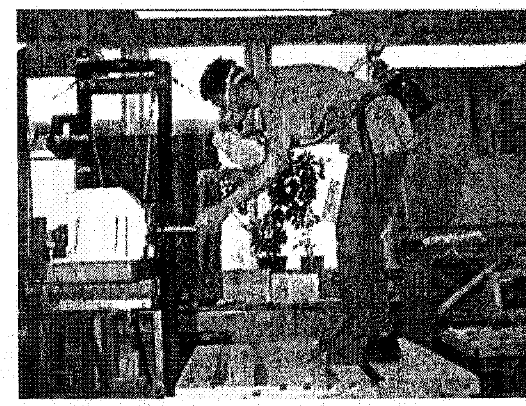
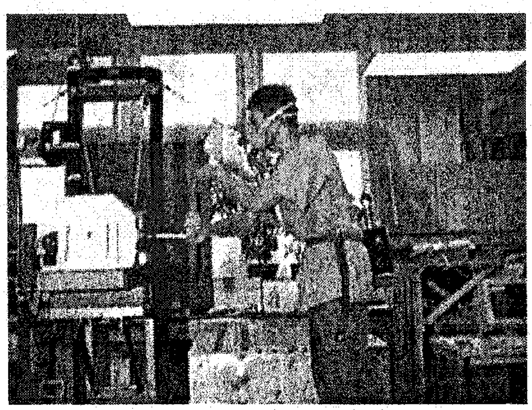


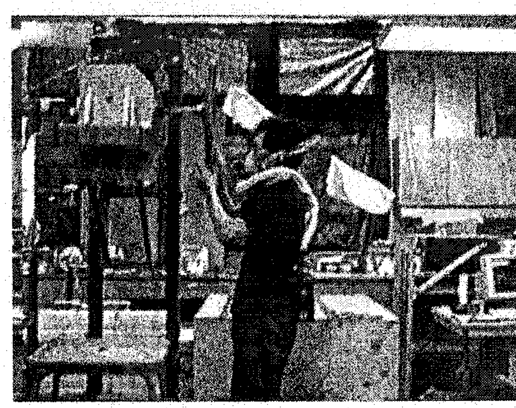
A. 58 cm Distance, 35 cm height (squat)



B. 58 cm Distance, 35 cm height (stoop)



C. 58 cm Distance, 93 cm height



D. 19 cm Distance, 168 cm height

Figure 9.3: Examples of participants performing the dynamic handwheel actuation task in experiment 2. A. 58 cm Distance, 35 cm height (squat). B. 58 cm Distance, 35 cm height (stoop). C. 58 cm Distance, 93 cm height D. 19 cm Distance, 168 cm height.

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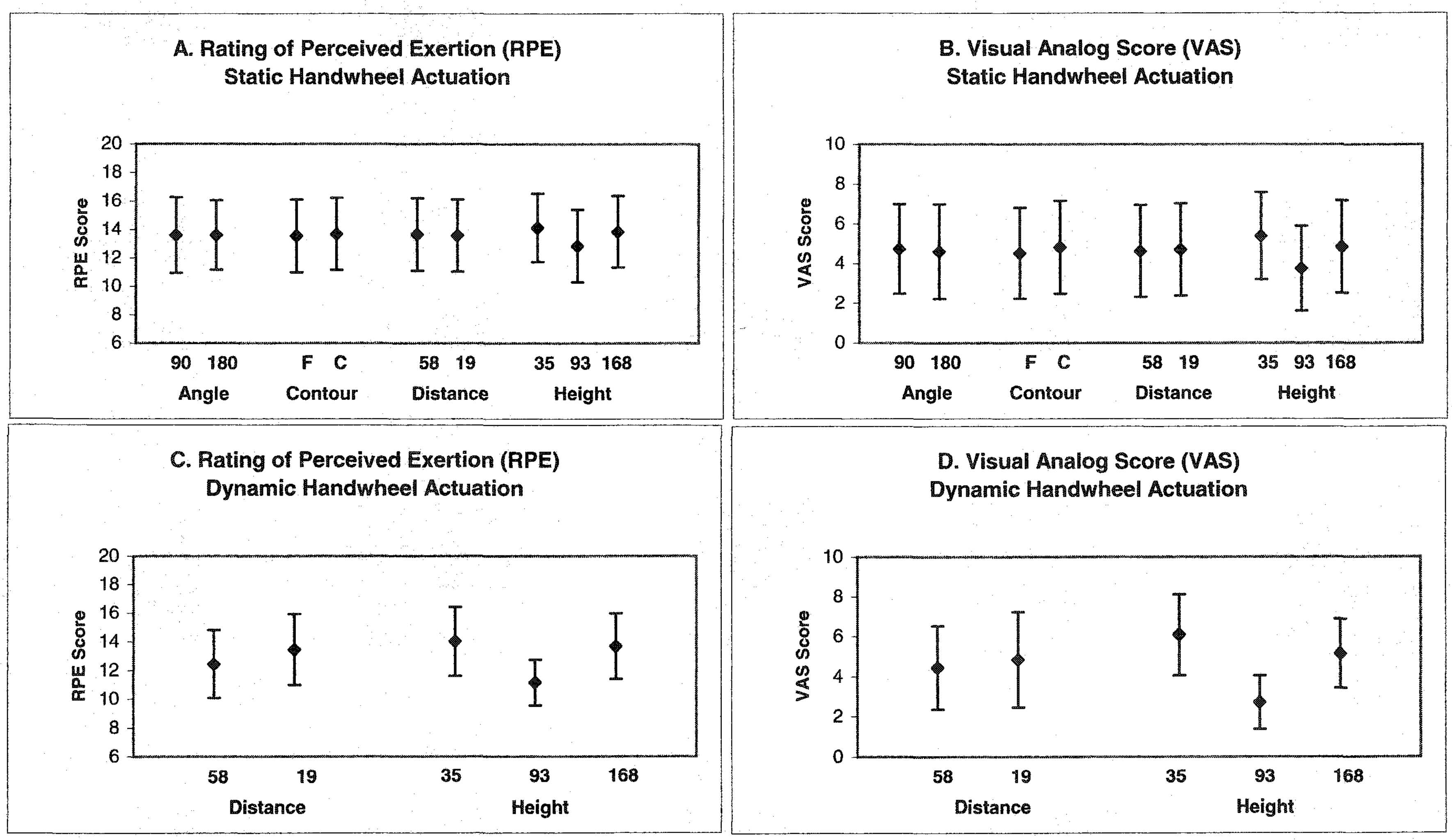

Figure 9.4: RPE and VAS scores for static (A and B) and dynamic (C and D) handwheel operation. F = flat, C = curved, distances and heights are measured in cm. Error bars represent the standard deviation.

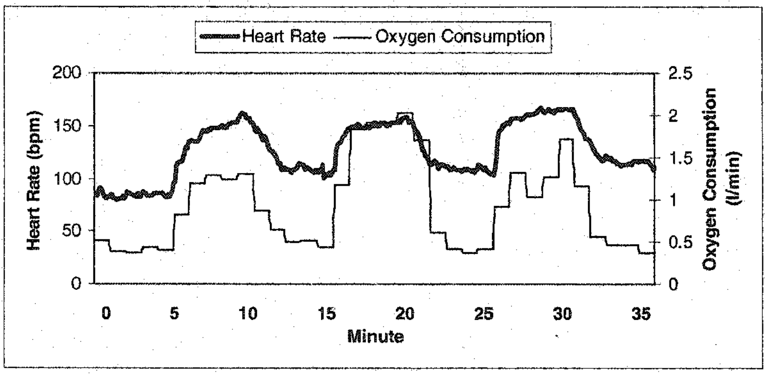

Figure 9.5: Example of the heart rate and oxygen consumption observed for one 35-minute experimental trial.

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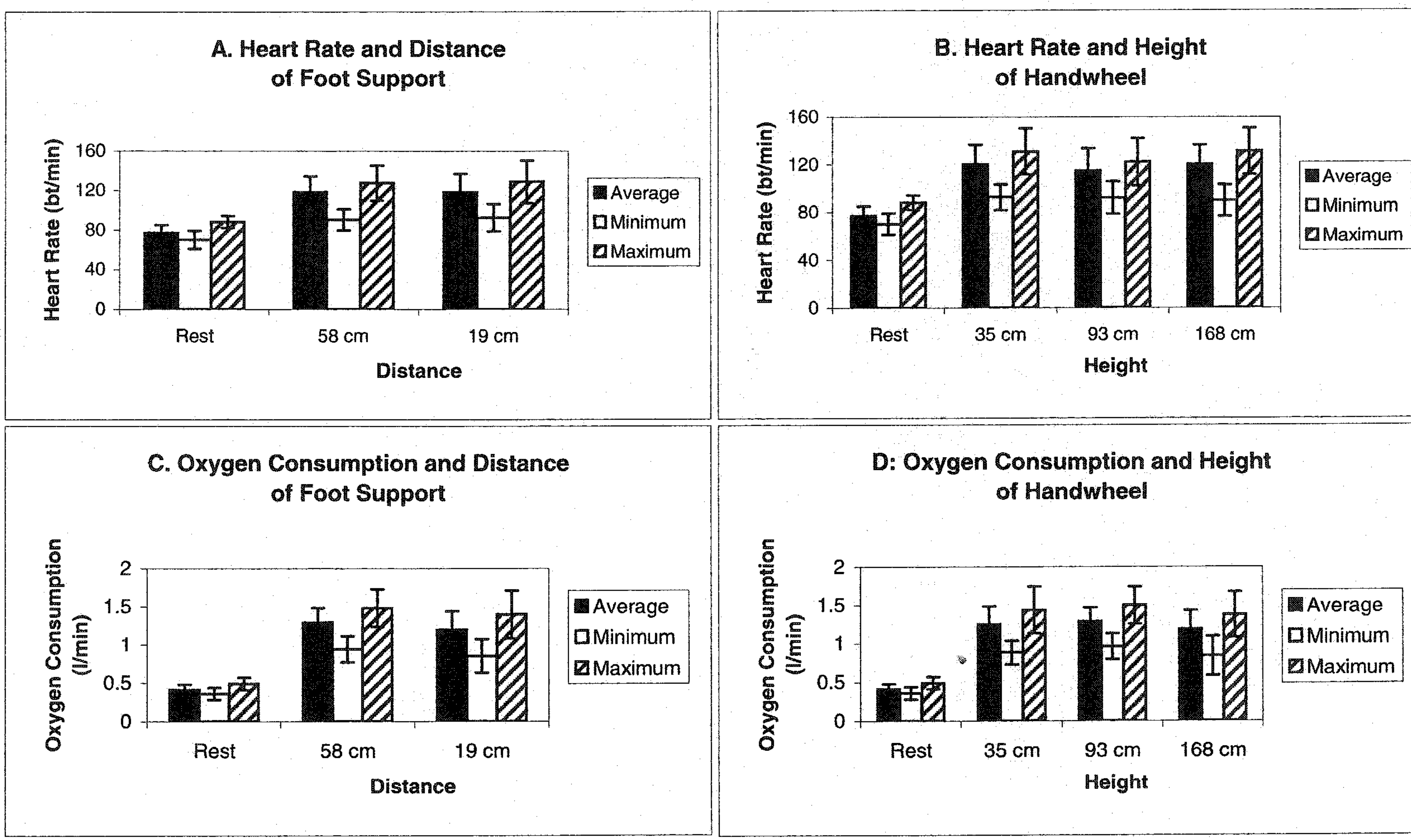

Figure 9.6: The effect of distance of foot support and handwheel height upon heart rate and oxygen consumption. A. Heart rate and distance of foot support. B. Heart rate and height of handwheel. C. Oxygen consumption and distance of foot support. D. Oxygen consumption and height of handwheel.

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Chapter 10

General Discussion

10.1 Summary and Contribution of the Thesis

The negative impact of occupational injury and illness upon industry is profound, particularly with respect to those afflictions affecting the musculoskeletal system (Kumar 2001; Marras 2000; Keyserling 2000a & b; Wulff *et al.* 1999a & b; Waters *et al.* 1993; Deyo *et al.* 1991). Thus it is apparent that any intervention targeted at reducing the effect of this impact, through a reduction in the frequency and severity of incidents ultimately leading to control and prevention would be desired. What is presented in this thesis is a logical, systematic approach to attaining this goal by focusing upon one particularly hazardous occupational task that workers are required to perform. This required establishing the need for such an intervention and justifying the methods to be utilized. This was followed by the in-depth analysis of the task from all possible perspectives.

A template for integrating an existing proven method of control and prevention (ergonomics) within the corporate culture and loss management philosophy at the plant and organizational level of industry was put forth. This was the first time such an approach has been formulated and published in the applied scientific literature. Furthermore, it lays out a path for their integration that represents the beginning of a symbiotic partnership between the two disciplines that until recently operated separately, if they operated at all concomitantly. The common link between the two disciplines in the majority of instances is the occupational injury and illness surveillance system. Whenever proper design considerations were not implemented or not available during the construction of facilities, tools or equipment, then this system serves as a means to identify targets for intervention, and also as a means of evaluating the success of such interventions. The agreement between two currently employed passive surveillance systems in one industrial organization was shown to be marginal and inconsistent. The results of this case study assessment indicated that one integrated organization-wide surveillance system is desired to alleviate problematic issues such as coding and

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information sharing. Furthermore, since the two systems were not in agreement, there is an inherent risk of improper managerial decisions. This could have affected the justification for, and evaluation of, interventions targeted at controlling and preventing incidents. As a result, some interventions may have been successful yet the benefit was not reflected due to the use of a poorly designed, implemented and maintained surveillance system. The observations of Courtney *et al.* (1997) support these findings and recommendations.

The loss management program and accompanying surveillance system (loss control reporting system) were used to identify one of the most hazardous occupational tasks workers within a mid-sized industrial organization were required to perform. The task selected was that of handwheel actuation. Through a systematic search of the scientific literature, it was revealed that currently existing standards and guidelines for the design of this task were insufficient. More importantly, the task has received little attention by the scientific community and hence was a novel area of study. In addition, some of the studies that have been conducted were incomplete and have not addressed major areas of concern such as the electromyographic (EMG) activity exhibited during handwheel actuation. It was also revealed that the task was common to many other industries besides the petroleum industry, hence allowing for a much broader application of the results of the studies.

The analysis of workers completing the task in the field served as a means to develop and base more robust laboratory-based experiments involving handwheel actuation and operation. It was revealed that stop-check valve handwheels induced 48%, 98% and 141% more EMG than the other handwheels and that the flexor carpis radialis and erector spinae muscles were very active in this task. The stop-check valve handwheel, which required repeated forceful exertions to operate, was perceived to be the most difficult and the most uncomfortable to operate by the workers. These findings corroborate with the data obtained from the surveillance system, which identified this task as hazardous, as well as from unstructured interviews with workers who cited this task as the most problematic for them. Furthermore, these findings support the results of the detailed literature search that this task poses significant risk of injury to the upper extremity and low back of the operator (Woldstad *et al.*, 1995; Mcmulkin & Woldstad

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1995; Johnson & Woldstad 1993; Jackson *et al.*, 1992). This in light of the fact that the most difficult handwheels were not permitted to be studied and that some of the handwheels could not be operated, and hence examined, by all operators.

A series of experiments were carried out to determine the effect of various variables such as trunk posture, upper extremity position, handwheel height above grade, and pitch angle orientation upon maximal strength, EMG activity, perceived exertion, oxygen consumption and heart rate. The study of strength and EMG activity revealed that upper extremity adduction strength, which is a motion that contributes to the generation of maximal net tangential forces during handwheel actuation, was not affected by large levels of axial trunk rotation. However, upper extremity position was, and the flexor carpis radialis muscle was again shown to exhibit significant EMG activity, as was found in the field study. This implies a principal contributory role in the adduction action, as well as in the handwheel actuation action.

The flexor carpis radialis muscle was also found to contribute significantly to the action of simulated handwheel actuation. In addition, the high levels of activity of the erector spinae muscle observed during handwheel actuation also corroborated with the results obtained in the field study. Since these were the first studies to utilize the invaluable tool of EMG analysis to assess handwheel actuation no comparisons to past research can be made. However, the results do conform to biomechanical logic. The issue of the maximal two-handed counter-clockwise net tangential force the participants were capable of exerting upon the stationary handwheel was studied in conjunction with the EMG activity. These values were significantly below those forces typically required to actuate handwheels in the field (Amell & Kumar 2001; Parks & Schulze 1998; Jackson *et al.*, 1992). Hence, it is not surprising that overexertion injuries to the musculoskeletal system commonly result from this task (Parks & Schulze 1998). Therefore to control for these types of injuries, the static 'cracking' force demands of the task should reside well below 700 N. This information should be assimilated with the results of McMulkin & Woldstad (1995) regarding handwheel rim shape in order to procure a safer overall design.

With respect to the risk of injury to the low back during handwheel actuation, it was revealed that based upon past research into the phenomena (Marras 2000; McGill

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1997; Waters *et al.*, 1999; Waters *et al.*, 1993), the force demands of this task exceed the tolerances of the structures that comprise this anatomical region. Handwheel pitch angle and height above the grade significantly affected the compression as well as shear forces acting upon the low back. Hence, the results of this experiment indicate that this task may be hazardous to the low back and that as high as 99% of the referent population is incapable of generating sufficient upper extremity strength to safely complete the task. Since the external biomechanical load was generated by the participants and then input into the 3D model, one would predict that the task would have been predicted safe. However, this was not the case and the task as examined was unsafe, which indicates that should the external load during handwheel actuation in the field (up to 400 Nm of torque requiring 2000 N of equivalent tangential force when the experimental setup is considered) be input, the task would surely impart hazardous levels of spinal loading. Hence these results are in agreement with the outcome of the field study as well as those studies reviewed in the systematic search of the literature.

It should be reiterated that, based upon review of the scientific literature, the experiment utilizing a 3D biomechanical model to investigate simultaneous pushing/pulling and lifting/lowering of loads at the hands was of its kind (De Looze *et al.*, 2000; Shoaf *et al.*, 1997; Lee *et al.*, 1989). All other studies have investigated motions where the hands moved in parallel directions. As a result, less of a load would be expected to be imparted upon the structures of the low back since the force vectors are essentially canceling one another out. In light of this observation, the task remained unsafe which speaks to its inherent hazards.

Experiments were undertaken from perspectives other than biomechanical or electromyographical. These experiments investigated the task of handwheel actuation and operation from a psychophysical and physiological perspective. Rather than limiting the analysis to static actuation ('cracking'), dynamic operation was also studied in the laboratory, just as it had been in the field study. It was revealed that a handwheel height of 93 cm from the grade induced the least amount of perceived exertion during both actuation and operation. The physiological data revealed the task to be very heavy work, based upon observed levels of oxygen consumption and heart rate. The results indicate that the task imparts a profound psychophysical and physiological load on the worker and

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that these factors must be considered in the design of such control devices in an effort to optimize the fit between this task and the worker.

The research studies undertaken and discussed in this thesis independently confirm from biomechanical, psychophysical and physiological perspectives that the task of industrial handwheel actuation does indeed impart a heavy work load. Such a work load has been shown to induce musculoskeletal injury or illness in workers (Kumar 2001; Keyserling 2000a & b; Marras 2000; Waters *et al.*, 1993). Hence, these findings are in agreement with the outcome of the surveillance system analysis, as well as from discussions with operators in the form of unstructured interviews which indicated this task to be a significant hazard. Similar findings were put forth by Parks & Schulze (1998), as well as discussed by several other authors including Meyer *et al.*, 2000; Wood *et al.*, 1999/2000; Schulze *et al.,* 1997a & b; Shih & Wang, 1997; Shih *et al.*, 1997; Woldstad *et al.*, 1995; McMulkin & Woldstad, 1995; Johnson & Woldstad, 1993; Jackson *et al.*, 1992; Raouf *et al.*, 1986; and Raouf *et al.*, 1984. Since the task is proven hazardous, and design-based interventions targeted at improving the match between the size and capability of the worker and the task have been successful in the past (Lincoln *et al.*, 2000; Bernacki *et al.*, 1999; Brisson *et al.*, 1999), they are the preferred method of addressing the root cause of this occupational hazard.

The existing standards and guidelines for handwheel actuation are insufficient, and past research was incomplete in many respects (Amell & Kumar, 2001). As a result, gaps in our knowledge of this task were apparent. The work undertaken in this thesis has uncovered new and significant information which has contributed and added to our understanding of the biomechanical, and the electromyographical characteristics of handwheel actuation, as well as the psychophysical and physiological loads imparted upon the operator by this task. This work has revealed that the three handwheel heights investigated did not affect the maximal two-handed isometric net tangential strength to a significant degree, a finding also reported by Schulze *et al.* (1997a) and Wood *et al.* (1999/2000). The distances investigated by these authors were not large. It was hypothesized that differing body kinematics were utilized at the various heights to account for these differences. The effect of extreme handwheel heights has yet to be studied, however. it is postulated that at the lowest and highest handwheel heights

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possible, significantly less force will be developed (Parks & Schulze, 1998). At the highest heights, where the operators may only be able to grasp the handwheel, not much more force than their body weight would be applied when the handwheel is in the vertical orientation, similarly at the lowest height; similar constraints are expected due to constricted postures. This brings forth the issue of handwheel pitch angle; the vertical orientation (90^o) is superior to handwheels requiring operation in other planes. In addition, more force could be generated when participants had an ample distance of foot support thus giving credence to facility designs without constricted workspaces, contrary to the majority of existing process facility designs.

In addition to these biomechanical results, the vertical handwheel orientation coupled with the middle height above grade (93 cm) induced the least psychophysical and physiological load in the operator. There has only been one other similar study published in the literature, and the results obtained in this thesis corroborate their findings, although this study was not as broad nor as thorough as those reported herein (Meyer *et al.* 2000). In addition, our study included a 150% longer task time than was investigated in this study and included handwheel heights above the grade that varied much more; as a result our simulation more closely reflected real-world situations common to petroleum refineries and other process facilities.

Thus with respect to the most pressing questions requiring further research as outlined in the systematic review of literature produced by Amell & Kumar (2001), the research reported in this thesis provides scientifically rigorous and acceptable answers to questions 1 through 5, while question 6 remains unanswered and worthy of further study. Thus these studies further our understanding of the cause of occupational musculoskeletal injuries and illnesses sustained by operators of industrial handwheels, as well as provide possible avenues for design-based interventions targeted at the root cause of these afflictions.

In addition to these research studies, the work carried out on the integration of ergonomics and loss management and their dependence upon surveillance in existing facilities also contributes to the goal of occupational injury and illness control and prevention and contributes to our overall knowledge concerning the management, identification, justification and evaluation of ergonomic interventions.

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The assimilation of the information gained from the studies presented herein is necessary to gauge the contribution of this thesis to the scientific knowledge base. Justification for the integration of ergonomics, which is based upon sound scientific principles and loss management, an established business practice, is important in concerted efforts to control and prevent occupational injuries and illnesses. In instances where ergonomic principles were not applied in the design stage, surveillance becomes an important tool, and hence proper surveillance is crucial. This thesis introduced the concept of integrating these two disciplines and reiterated the need for sound surveillance practice, a topic much neglected in the ergonomic literature. The results of the surveillance system comparison solidified the justification for such a set of procedures. Although an industry free of occupational injury and illness is the desired goal, such an outcome cannot come without explicit concerted efforts on behalf of all concerned parties. In this body of work, we opted to start off with one particular hazardous task (of many) and investigate it from all possible perspectives for the purpose of controlling and preventing musculoskeletal injuries and illnesses in future facilities utilizing handwheel-based control devices to regulate processes and systems. Hence the true evaluation of this body of work will come after several years, after the facilities have been constructed, commissioned, brought online and the biomechanical, anthropometric, physiological and psychophysical characteristics and capacities of the process operators are matched with this newly designed occupational task. We believe that the results of these studies, when implemented, will alleviate substantial risk from this task and improve the working life of those workers charged with carrying out this task.

10.2 Limitations of the Thesis

There are limitations to the research presented in this thesis. Since not all possible ranges and combinations of variables known or thought to contribute to the task of handwheel actuation were examined, it is difficult to predict with accuracy whether all musculoskeletal injuries can be controlled and prevented using these data. Caution is recommended and must be exercised when interpreting the results of this research, particularly due to the fact that it was conducted in a laboratory setting under controlled

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circumstances and hence may lack some degree of external validity. Nevertheless, the experiments that comprise this thesis have a high degree of internal validity, did reveal new discoveries and can serve as a basis for future research in the area of industrial handwheel actuation and its relationship to worker capacity and capability.

10.3 Future Research

Although every effort was made to study the problem in depth, and this was proven to be successful, some variables could not be examined in the course of this body of research due to practical concerns such as time and budget. The focus of future research should build upon the results obtained in the present studies. Optimal handwheel diameter should be carefully weighed against the torque requirements and the anthropometrics of the process operator. Ideally, the largest handwheel possible should be used to decrease the net tangential force requirement while maintaining high torque production, however large sizes cannot always be utilized, hence more research is needed to determine the optimum diameter. Other handwheel types should be studied in a laboratory setting, particularly the stop/check handwheels observed in the field study as these require high impact forces hence alternative designs should be sought. The kinematics of the whole body, and its effect upon kinetics during handwheel actuation and operation in the field should be examined in order to determine optimum techniques to be taught to the workers in combination with proper task design. The effect of repeated industrial handwheel actuation upon the occupational health status of the operator over the course of a shift, work week or perhaps even career should be examined. Finally, the electromyographic activity of the latissimus dorsi and triceps brachii should be studied in order to test the hypothesis that these muscles may be significantly active, and perhaps overloaded and at risk of overexertion.

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