A multivariate statistical model for whole-body related musculoskeletal disorders
by Harish Yerneni

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Industrial and Management Engineering
Montana State University

Abstract:
The incidence of work-related musculoskeletal disorders (MSDs) continues to be a key concern for occupational safety and health care professionals. Several factors such as repetition, forceful exertion, and awkward postures have been linked to their development. While these links have been well established, valid and reliable techniques for measuring MSD risk are lacking, particularly for jobs in non-manufacturing industries or non-repetitive jobs in general.

Marley, et. ah, (1997) examined such jobs in the power distribution industry with a goal of better understanding which work factors may be associated with MSDs. Injury data from over 2000 workers in one company were tabulated by job classification (12 total categories). Three representative categories, electric line crews, gas line crews, and meter readers were identified as having high, medium, and low risk for injury respectively, based on the recorded rate of MSDs in these categories. An ergonomic/work-methods analysis was then performed upon 5 key activities within these jobs. Activities were further broken down into 31 required tasks (e.g., climb pole, make connection, shovel, cut pipe, etc.) and even further into 18 fundamental work elements (e.g., various body postures, grasp type, force level, duration, terrain condition, etc.).

Cluster analysis involving the work element measures resulted in five clusters. Two clusters generally represented upper and lower part of the upper extremities, two clusters generally represented lower extremities and one contained miscellaneous ergonomic variables. All the coefficients of the cluster variable weights in the five clusters resulted in the same sign from principal component analysis I, signifying that the increase in values of any cluster variable in turn increases cluster score and hence the risk level. The clusters are modeled and validated using ordinal logistic regression technique. The model accurately predicted 92% and 76.5% of training and testing data sets respectively. A user-friendly web application of this model targeting the novice user has been developed.

The model needs should be trained with larger data sets for better prediction and more robust applications. However, the current model may be useful for predicting the whole-body related MSDs in the utility industry and comparable non-repetitive jobs. The identical clusters may also be useful in the understanding of physical job stress in these environments.

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APPROVAL

of a thesis submitted by

Harish Yerneni

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

The incidence of work-related musculoskeletal disorders (MSDs) continues to be a key concern for occupational safety and health care professionals. Several factors such as repetition, forceful exertion, and awkward postures have been linked to their development. While these links have been well established, valid and reliable techniques for measuring MSD risk are lacking, particularly for jobs in non-manufacturing industries or non-repetitive jobs in general.

Marley, et. al., (1997) examined such jobs in the power distribution industry with a goal of better understanding which work factors may be associated with MSDs. Injury data from over 2000 workers in one company were tabulated by job classification (12 total categories). Three representative categories, electric line crews, gas line crews, and meter readers were identified as having high, medium, and low risk for injury respectively, based on the recorded rate of MSDs in these categories. An ergonomic/work-methods analysis was then performed upon 5 key activities within these jobs. Activities were further broken down into 31 required tasks (e.g., climb pole, make connection, shovel, cut pipe, etc.) and even further into 18 fundamental work elements (e.g., various body postures, grasp type, force level, duration, terrain condition, etc.).

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CHAPTER 1

INTRODUCTION

Cumulative Trauma Disorders (CTDs) is defined as physical injuries that develop over a period of time as a result of repeated biomechanical or physiological stresses on a specific body part. In short, CTDs are disorders of softer tissue due primarily to repeated use. CTDs are often considered to be work-related. Assessing the risk or determining the onset of a CTD is very difficult (Naderi and Ayoub, 1989). CTDs occur because of a single overexertion event or frequent exertion over a period of time.

Cumulative Trauma is often referred to in the literature by a number of different terms. Other terms used to describe the same condition are repetitive trauma injuries (RTI), repetitive strain injuries (RSI), musculoskeletal disorders (MSDs), occupational overuse syndrome, osteoarthroses and degenerative joint disease (Armstrong, et. al, 1986; Salter, 1970; Silverstein, et. al, 1986). CTDs are commonly reported in the tendons, and in the nerves of upper extremities, including the fingers, the wrist, the forearm and the upper arm, and the shoulder. Vern Putz-Anderson (1988) identifies three major types of disorders according to an anatomical view: tendon disorders, neurovascular disorders, and nerve disorders.

A majority of the occupational factors causing CTDs can be characterized as involving one or more of the following components: awkward postures of the wrist or shoulders, excessive manual force, and high rates of manual repetition (Putz-Anderson,

1988). It is generally accepted that force, repetition, posture, recovery time and type of grasp are important factors in the causation of distal upper extremity disorders (Moore and Garg, 1995). Some other job factors that increase risk in combination with the other factors include cold temperature, use of gloves, use of vibrating tools, etc. (Moore and Garg, 1995). Even though not studied in detail with regard to distal upper extremity disorders, duration of exposure, static muscular work, and use of the hand as a tool are also generally accepted as risk factors (Moore and Garg, 1995).

CTDs have become a prevalent form of injury in modern industry. The Bureau of Labor Statistics (BLS, 2002), US department of Labor, states that in 2000 when looking specifically at work-related musculoskeletal disorders, 66.7% (241,800) of all illness cases were due to disorders associated with repeated trauma.

Evaluation of assessment methods plays an important role in strategy to reduce and control MSDs. There are certain techniques to aid the ergonomist in understanding and identifying CTDs problem areas. They can be classified primarily into two categories: trailing and leading indicators. Trailing indicators are defined as measures that document injuries after the fact. Examples include injury rate statistics, lost time statistics, cost data, etc. Trailing indicators should be viewed as benchmark data by which system design will ultimately be judged. Trailing indicators are not, by definition, predictive. By contrast, "leading indicators" are measures that aid the ergonomist in assessing *potential* ergonomic concern. Leading indicator methodologies are useful for regular monitoring or auditing for CTDs risk. One such methodology is self-report, often used for inter and intra task comparisons. These data can be correlated with other

statistical trend data. One such technique known as the "Body Map" was developed by Marley and Kumar in 1996 and has been shown to be a reliable "leading indicator" of CTD risk for the whole-body. Another well-known technique is Rapid Upper Limb Assessment (RULA), which is a survey method for the investigation of work-related upper limb disorders (McAtamney and Corlett, 1993). Both these methods take repetition into account.

These models revealed that MSD risk is likely due to some combination of force application and awkward postures. Most knowledge has been derived from examination of repetitive manufacturing or office environments and with one variable at a time constraint. Thus, valid and reliable evaluation techniques for MSD risk are lacking though some reasonable attempts have been made. This is particularly true for jobs in non-manufacturing industries or otherwise classified as non-repetitive. Thus, the main objective of this study is to develop a model for whole-body related MSD for non-repetitive jobs or otherwise known as jobs in non-manufacturing industry.

CHAPTER 2

REVIEW OF THE LITERATURE

Cumulative Trauma Disorders

This chapter is devoted to exploring the literature dealing with cumulative trauma disorders. It discusses in detail, different types of CTDs and occupational risk factors causing them. Finally, currently available statistics relating to CTDs are provided.

Cumulative Trauma Disorders (CTDs) is defined as physical injuries that develop over a period of time as a result of repeated biomechanical or physiological stresses on a specific body part. CTDs is a collective term for syndromes characterized by discomfort, impairment, disability or persistent pain in joints, muscles, tendons and other soft tissues (Kroemer, 1989). The major distinction between a CTD and sprain or strain injuries is that CTDs cannot typically be traced to a single incident, i.e., a slip or fall resulting in an acute trauma.

However, it is true that a significant stressful event may trigger diagnosis of the condition. Thus, assessing the risk or determining the onset of a CTD is very difficult (Naderi and Ayoub, 1989). It is clear that CTDs occur because of a single overexertion event or frequent exertion over a period of time. Figure 1, adapted from Chaffin and Anderson (1999) describes the spinal motion segment failure for both over exertion and

frequent exertion cases in top and bottom graphs, respectively. However, the same concept of CTDs can be extended to all body areas without loss of generality.

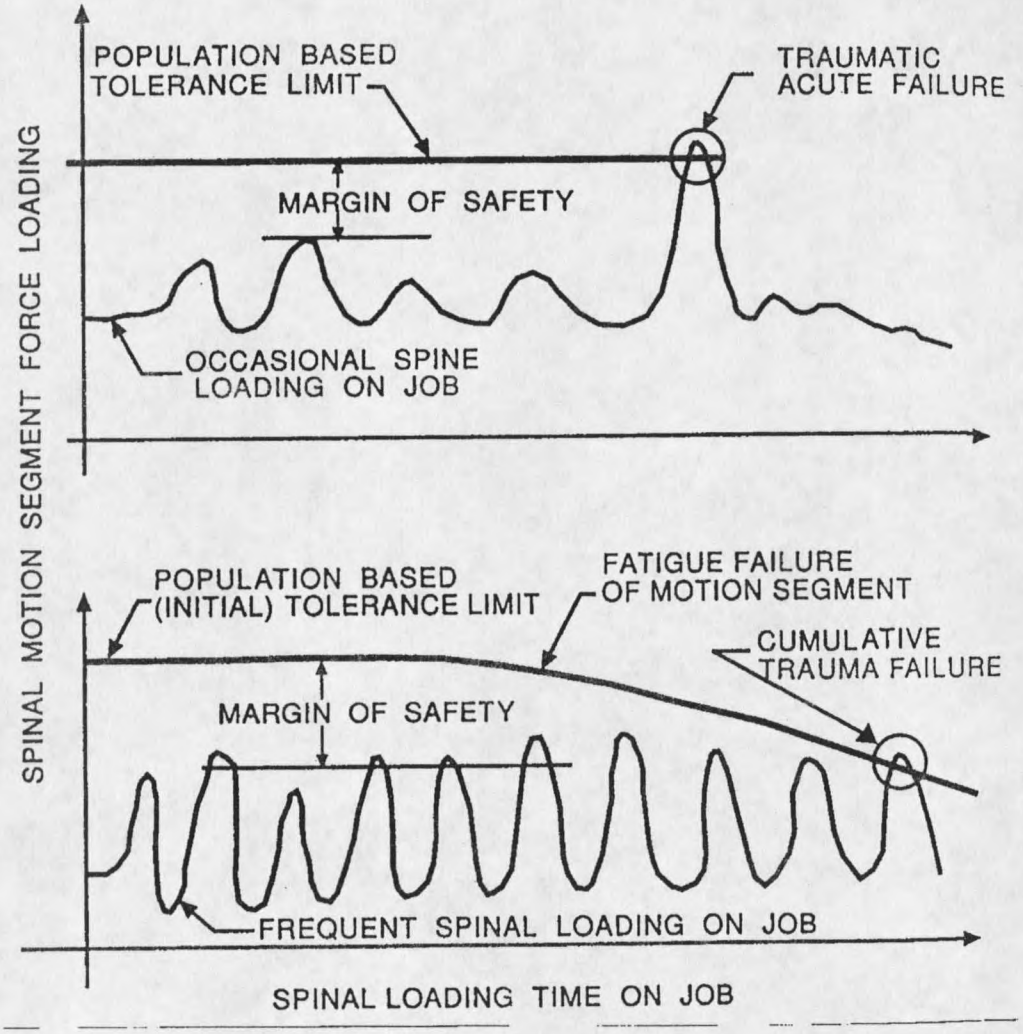

Figure 1 Depiction of spinal motion segment failure

Cumulative Trauma is often referred to in the literature by a number of different terms varying from discipline to discipline and from country to country. Other terms used to describe these disorders include repetitive trauma injuries (RTI), repetitive strain injuries (RSI), musculoskeletal disorders (MSDs), occupational overuse syndrome, osteoarthroses and degenerative joint disease (Armstrong, et. al, 1986; Salter, 1970; Silverstain, et. al, 1986). From now onwards, the author will use CTDs and MSDs interchangeably.

There are many forms of upper extremity musculoskeletal disorders, and different authors have classified them into different categories. Vern Putz-Anderson (1988) identifies three major types of disorders according to an anatomical view: tendon disorders, neurovascular disorders, and nerve disorders. Other authors classify them as alterations of the muscle-tendon unit, the peripheral nerves, or the vascular system (Grieco, et al., 1998). Muggelton, Allen and Chappell categorize upper extremity disorders as falling into one of the following three categories: vibration white finger and related dysfunctions; nerve compression disorders; and tendon and tendon-tendon related disorders (1999). Feurstein, et. al., call them nerve entrapment, tendon, or musculoskeletal-related disorders (1998). Though the terminology differs, the basic classifications are very similar. For the purpose of this report, the author has selected three classification groups: tendon disorders, vascular and neurovascular disorders, and nerve disorders.

Tendon Disorders

Tendons attach muscles to bone and transfer forces and movements from the muscles (Chaffin, Anderson, &Martin, 1999; Putz-Anderson, 1988). Tendons are surrounded sheaths of fibrous tissue in areas where friction could potentially be a problem (Chaffin, et. al., 1999). The sheath has an inner lining, the synovius, which produces synovial fluid, a lubricant that facilitates gliding of the tendon (Chaffin, et. al., 1999). The tendon glides back and forth in the sheath as the muscle contracts and relaxes. With accustomed overuse, the lubricating fluid in the tendon sheath may be lessened causing friction between the tendon and the sheath (Putz-Anderson, 1988). The tendon area then feels warm, tender and painful, signaling the onset of inflammation (Putz-Anderson, 1988). Inflammation is an immune system response by the surrounding tissue and blood vessels designed to limit bacterial invasion and initiate repair (Putz-Anderson, 1988). Swelling and sensation of the warmth occurs in the injured tissue from the inflow of blood (Putz-Anderson, 1988). Tendon disorders can include: tendonitis and tenosynovitis (Atcheson, 1988; Feurstein, et. al., 1988; Gordon, 1995; Greico, et. al., 1998; Fernandez & Marley, 1988, Muggleton, et. al., 1999; Putz-Anderson, 1988), as well as bursitis, and ganglionic cysts (Fernandez & Marley, 1988, Fernandez & Marley, 1988).

Tendinitis and Tenosynovitis. Tendinitis refers to tendon inflammation specifically, whereas tensosynovitis is a general term describing injury involving the tendon sheath (Muggleton, et. al., 1999). Ranney further defines the two as tendonitis being inflammation as a result of microtears, and tenosynovitis as inflammation resulting

from friction (1993). These conditions are most commonly found in the flexor and extensor tendons of the wrists and thumbs, the extensor tendons of the elbow, and the rotator cuff and biceps tendons of the shoulders (Herrington & Morse, 1995). It is most likely to occur in areas where the tendon is restricted by anatomical feature (i.e., bony channels and tunnels) (Fernandez & Marley, 1998). This form of tendon inflammation occurs when a muscle/tendon unit is repeatedly tensed, then with further exertion tendon fibers may fray or tear apart (Gordon, 1995; Putz-Anderson, 1988). If this happens, the tendon becomes thickened, bumpy and irregular (Putz-Anderson, 1988). The repetitiveness of the task, the force required, and the position of the joint are all factors in the pathogenesis of this problem (Gordon, 1995). Since tendons have virtually no blood supply, they are not capable to repair themselves, thus damage can become instrumental (Pecina & Bojanic, 1993), and without rest and sufficient time for the tissues to heal, the tendon may be permanently weakened (Putz-Anderson, 1988).

Tenosynovitis is a general term for a repetitive-induced tendon injury, which involves the synovial sheath (Putz-Anderson, 1988). With extreme repetition, the sheath will produce unnecessarily large amounts of synovial fluid that accumulates and causes the sheath to be swollen and painful (Putz-Anderson, 1988), resulting in an inflammatory reaction within the tendon sheath (Fernandez & Marley, 1988).

Stenosing tenosynovitis is another type of tensosynovitis, that may be diagnosed if the tendon becomes irritated and rough, and if the sheath becomes inflamed and presses on the tendon (Muggleton, et. al., 1999; Putz-Anderson, 1988). DeQuervian's disease is the most recognized stenosing tenosynovitis. It is a disorder that affects the tendons on

the side of the wrist and at the base of the thumb (Muggleton, et. al., 1999; Putz-Anderson, 1988). These tendons are connected to muscles on the back of the forearm and contract to pull the thumb back and away from the hand (Putz-Anderson, 1988). De Quervian's disease is attributed to excessive friction between two thumb tendons and their common sheath (Putz-Anderson, 1988).

If the tendon sheath of a finger becomes exceedingly swollen, it can cause the tendon to get locked in the sheath, then attempts to move the finger result in snapping and jerking movements, called stenosing tenosynovitis crepitans or "trigger finger" (Muggleton, et. al., 1999; Putz-Anderson, 1988). In later stages of the disease, snapping ceases and the finger remains permanently locked (Muggleton, et. al., 1999). The palm side of the fingers is the usual site for trigger finger. This disorder is often associated with using tools that have handles with hard or sharp edges (Putz-Anderson, 1988).

Bursitis. Bursae are anti-friction devices found throughout the body where bony prominences are close to the skin surface and friction from outside the body or where tendons and ligaments may rub against the prominences (Rowe, 1985). In the presence of high degrees of friction, the bursae will oversecrete lubricating fluids and bursal sacs will become enlarged and distended. If friction persists, the walls of the sac will thicken and become inflamed (Fernandez & Marley, 1998).

Ganglionic Cyst. Caused by the swelling of a tendon sheath with synovial fluid, a ganglionic cyst is common and is generally related to wrist usage (Birnbaum, 1986). Though rarely causing symptoms of nerve compression, such a cyst can often be painful

and is usually treated by aspiration or by surgical removal if the ganglion recurs (Fernandez & Marley, 1998).

Neurovascular Disorders

Neurovascular disorders are those CTDs which involve both the nerve and adjacent blood vessels

Thoracic Outlet Syndrome. Probably the most common form of neurovascular disorder is the thoracic outlet syndrome (Putz-Anderson, 1988). Thoracic outlet syndrome is a general term for compression of the nerves and blood vessels as they pass through the neurovascular bundle between the neck and shoulder.

Also known as cervicobrachial disorder, thoracic outlet syndrome is generally thought to result from heavy workloads combined with repetitive straining or unnatural static positioning of the arms (Sallstorm and Schimdt, 1984). Typical symptoms of thoracic outlet syndrome include numbness and tingling in the fingers and hand as well as a sensation of the arm "going to sleep." The blood pulse at the wrist may also become weakened.

Vibration Syndrome. Sometimes referred to as vibration induced white finger, Raynaud's syndrome, or traumatic vasospastic disease, vibration syndrome is characterized by episodes of blanching (whiteness or paleness) of the fingers due to closure of the digital arteries (Putz-Anderson, 1988). Due to the blockage of circulation in the fingers, coldness and pain is often associated with vibration syndrome (Taylor, 1974). This condition is caused by the transmission of vibration (varying in acceleration,

power, and frequency) from a tool to the hand. It is believed to be in part a vascular disturbance due to changes in the blood vessel walls and in part a nervous disturbance caused by reflex contraction of the smooth muscles of the blood vessels.

Nerve Entrapment Disorders

Carpal Tunnel Syndrome. Carpal tunnel syndrome (CTS) is one of the major forms of cumulative trauma disorders of the upper extremities (Putz-Anderson, 1988). Also described as occupational neuritis, partial thenar atrophy and median neuritis, CTS is generally attributed to insult, usually compression, to the median nerve within the wrist as it passes through the carpal tunnel (Armstrong and Chaffin, 1979a). This compression in turn is associated with repeated or sustained activities of the fingers and hands, often combined with the application of force, as well as pressure from hard work surfaces and sharp edges on hand tools (Feldman, et. al, 1983).

Occupational Risk Factors Causing CTDs

CTDs are often considered to be work-related. Majority of the occupational factors causing CTDs can be characterized as involving one or more of the following components: awkward postures of the wrist or shoulders, excessive manual force, and high rates of manual repetition (Putz-Anderson, 1988). It is generally accepted that force, repetition, posture, recovery time and type of grasp are important factors in the causation of distal upper extremity disorders (Moore and Garg, 1995). In addition to these factors, other job factors that combine to increase risk include cold temperature, use of gloves, use of vibrating tools, etc. (Moore and Garg, 1995). Even though not studied in detail

with regard to distal upper extremity disorders, duration of exposure, static muscular work, and use of the hand as a tool are also generally accepted as risk factors (Moore and Garg, 1995). Risk factors posture, force and repetition are discussed in detail in the following sections.

Posture

Certain jobs require the worker to assume a variety of awkward postures that pose significant biomechanical stress to the joints of the upper extremity and surrounding soft tissues. Awkward postures include any fixed or constrained body position. Other undesirable postures include those that overload the muscles and tendons, load joints in an uneven or asymmetrical manner, or involve a static load on the musculature (Putz-Anderson, 1988).

Force

The force required to perform various occupational activities is also a critical factor in contributing to the onset of CTDs. As the muscle effort increases in response to high task load, circulation to the muscle decreases causing more rapid muscle fatigue. When force requirements are high, recovery time can exceed actual work time. Deprived of sufficient recovery time, soft tissue injury will occur. Bones will break and skin and muscles will tear if the strain is too great. The mechanical stresses on the tendons and nerves produced by contact with sharp edges of hard objects are not quite obvious (Putz-Anderson, 1988).

Repetition

In general, a job is considered repetitive if the basic (fundamental) cycle time is less than 30 seconds or 50% (or more) of total cycle time performing the same fundamental task element (Konz and Johnson, 2000;Fernandez and Marley, 1998). These are the two generally accepted definitions of repetition.

Jobs that require the worker to perform highly repetitive motions also contribute to the onset of CTDs. The more repetitive the task, the more rapid and frequent are the muscle contractions. Muscles required to contract at a high velocity develop less tension than when contracting at a slower velocity for the same load. Hence, tasks requiring high rates of repetition require more muscle effort, and consequently more time for recovery, than less repetitive tasks. So, tasks with high repetition rates can become sources of trauma even when the required forces are minimal and normally safe (Putz-Anderson, 1988).

CTD Statistics

CTDs have become a prevalent form of injury in modern industry. The Bureau of Labor Statistics (BLS, 2002), US department of Labor, provides the following summaries related to CTD's. When looking specifically at work-related musculoskeletal disorders, BLS reports that in 2000, 66.7% (241,800) of all illness cases were due to disorders associated with repeated trauma. This figure does not include back injuries. BLS also reports that recently the number of cases of repeated trauma has decreased considerably,

lowering from 308,200 cases in 1995 to 216,400 cases in 2001—a 2.98% decrease as shown in Figure 2.

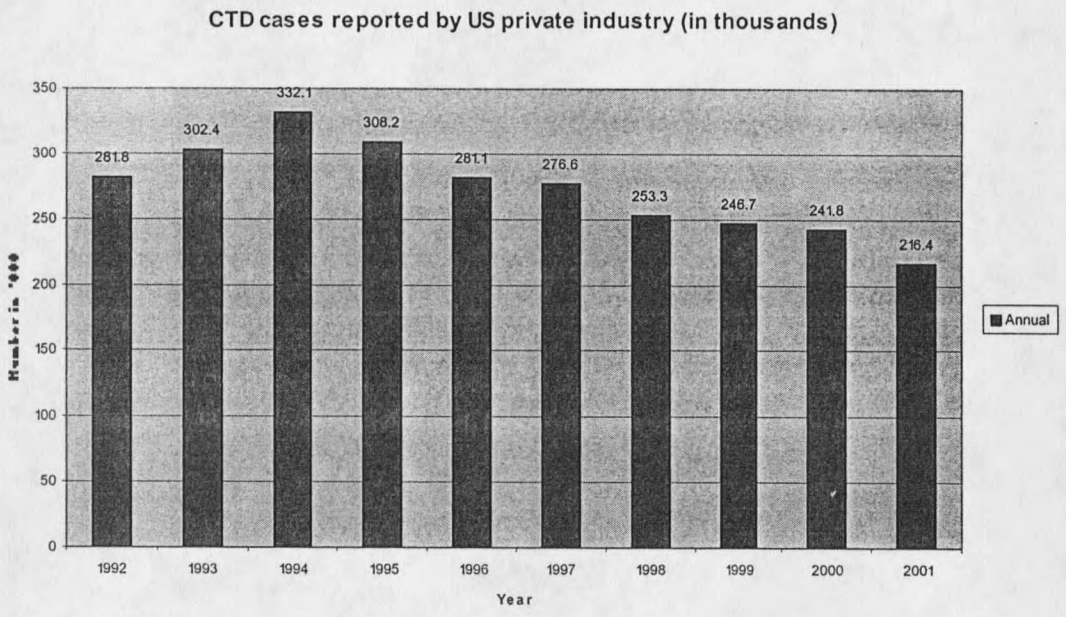

Figure 2 Number of CTDs reported in the US from 1992 to 2001

When looking specifically at cases involving days away from work, for which more detailed information is available, BLS reports that in 2000, approximately 32% or 523,043 cases were the result of overexertion or repetitive motion. This figure includes back injuries. Out of the repetitive trauma cases, 33% of injuries were due to manual lifting primarily affecting the back and over 32% resulted from hand tool use, data entry and repetitive grasping tasks. Cost estimates in the US vary from $13 to $20 billion annually (NIOSH 1996). In 1993, Webster and Snook estimated mean per case cost of compensable low-back pain at $8,321 and mean per case cost of compensable upper-

extremity CTDs at $8,070. Recent updates of these costs are currently not available but are believed to have risen substantially since 1993.

CHAPTER 3

OBJECTIVES

It has been shown that the number of musculoskeletal disorders (MSDs) has increased dramatically in recent years and has become a key concern for occupational safety and health care professionals. CTDs is also an ever increasing cost to business and industry in terms of reduced productivity, lost work time, high insurance and disability claims. Several factors such as repetition, forceful exertion and awkward postures have been linked to the development of work-related MSDs as discussed in Chapter 1. Thus, risk of MSDs is a critical concern for ergonomists.

Evaluation of assessment methods plays an important role in strategy to reduce and control MSDs. There are certain techniques to aid the ergonomist in understanding and identifying CTDs problem areas. The ergonomist should have access to certain "trailing indicators", which are defined as measures that document injuries after the fact. Examples include injury rate statistics, lost time statistics, cost data, etc. Trailing indicators should be viewed as benchmark data by which system design will ultimately be judged. Such indicators should also be analyzed thoroughly to look for undesired trends, or (hopefully) to verify that ergonomic changes are having the desired effect. Trailing indicators are not, by definition, predictive. By contrast, "leading indicators" are measures that aid the ergonomist in assessing *potential* ergonomic concern. Leading indicator methodologies are useful for regular monitoring or auditing for CTDs risk. One

such methodology is self-report, often used for inter and intra-task comparisons. These data can be correlated with other statistical trend data. One such technique known as the "Body Map" was developed by Marley and Kumar in 1996 and has been shown to be a reliable "leading indicator" of CTD risk for the whole-body. Another well-known technique is Rapid Upper Limb Assessment (RULA), which is a survey method for the investigation of work-related upper limb disorders (McAtamney and Corlett, 1993). Both these methods take repetition into account.

From the above models it can be inferred that, MSD risk is likely due to some combination of force application and awkward postures. Most knowledge has been derived from examination of repetitive manufacturing or office environments and with one variable at a time constraint.

Thus, valid and reliable evaluation techniques for MSD risk are lacking though some reasonable attempts have been made. This is particularly true for jobs in non-manufacturing industries or otherwise classified as non-repetitive. The activities within these jobs are varied with long cycle times. "Field crews" in utilities, for example. Further, many tasks in these activities may contain more than one known risk factor.

A method to examine MSD risk in non-repetitive, whole-body work is needed. Therefore a study was conducted to achieve the following.

1. Find the natural groupings of whole-body related musculoskeletal variables associated with CTDs using cluster analysis and further interpret the clusters.