Ergonomics of Single-Handed Pulling:

A Biomechanical and Psychophysical Assessment

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These six papers constitute Chapters 3 through 8 of this thesis.

Abstract

The description of biomechanical events measured during manual materials handling (MMH) activities has been a major focus for ergonomists attempting to understand the relationships between performance factors and injury mechanisms. Pulling exertions, while being frequently observed in occupational settings, requires more attention from researchers. The purpose of this work was to elucidate the influences of task-simulated factors upon subject performance while exerting pull forces within a stationary workstation.

In order to pursue these objectives, several methodological issues important to the systematic collection of laboratory-based pulling activities had to be resolved. Chapter 3 details work describing the capacity of subjects to exert maximal isometric forces, for three postural conditions (free standing, fixed standing and sitting), about diverse locations in the frontal plane. These data indicated that (a) the posture of an operator and (b) the location of the pull have significant effects upon the ability of a subject to produce forces and should be included as independent variables in future studies on pulling activities. Recommendations from this study conclude that single-handed pull exertions should be made at about elbow height in a parasagittal plane near the mid-line of the body in order to maximise force output. In Chapter 4, a psychophysical approach was employed to assess preferred workload outputs for persons exerting single-handed, submaximal isoinertial loads. The results from this study suggested that the ability of subjects to manipulate loads above 25% of absolute body mass becomes highly variable, and in some circumstances, unmanageable for repetitive handling tasks. Chapter 5 considers issues regarding the standardisation of foot positions during submaximal, repetitive dynamic pull exertions. Results indicated that positioning the contralateral foot (to the hand exerting the pull force) a distance of 20% stature from the frontal plane containing the origin of pull and 10% of stature laterally from the parasagittal plane containing the direction of pull and placing the other foot a distance of 25% of stature in the posterior direction from the most forward foot and on the parasagittal plane containing the line of pull would not significantly influence measures of load kinematics. This was in comparison to a condition in which subjects were free to choose his or her own foot orientations. These results support the use of standardised foot positions for future studies of submaximal, dynamic pulling activities. The initial work in this thesis provides a better understanding and description of pull origin locations about the frontal plane, load magnitudes and standardised foot orientations that would be necessary from an experimental control perspective.

The works in Chapters 6 through 8 investigated the effects of load magnitudes and force origins upon the manner that an operator exerts a pull, as described by trunk segment kinematics and electromyographic (EMG) activities of selected trunk and shoulder musculature. Chapter 6 revealed that magnitudes of 3-dimensional trunk kinematics during dynamic, submaximal pulls, as measured by a lumbar motion monitor, can be large, particularly in pull locations that are superior and lateral to the centre of mass of the subject. Magnitudes of axial rotation and trunk extension velocities were comparable to those observed for lifting activities thought to be associated with low back pain. In Chapter 7, the EMG activities of eight muscles (left and right erector spinae, left and right external obliques, right trapezius, right biceps brachii, right latissimus dorsi and right deltoid) were recorded for submaximal, isoinertial pull exertions. While co-activities of both agonist and antagonist muscles about the trunk were observed for all pull conditions, the muscles surrounding the shoulder joint were highly active. This would suggest that the muscles surrounding the shoulder complex are at a reasonably high risk for onset of fatigue and injury when recruited under similar demands *in situ*. Findings from the study highly recommend increased research attention upon the potential risk of injury of the shoulder during repeated pulling exertions. The effects of reach distance upon subjects located away from the frontal plane containing the origin of pull was examined in Chapter 8. The amounts and rates of axial rotation of the trunk observed in this experiment were similar to those considered to put a MMH operator at high risk for developing low back pain. EMG data provide support for the notion that the superficial muscles (the same muscles measured in Chapter 7) surrounding the shoulder complex are at risk for fatigue and injury, even though the workstation conditions were thought to be suitable in relation to the morphological characteristics of the subject.

It is evident that as the location of the origin of the pull moves superiorly in the frontal plane and towards more lateral parasagittal planes relative to the subject the biomechanical demands upon the operator increase. Results from these studies confirm the need to develop robust work practices guidelines pertinent to pulling activities.

Finally, the kinematic and electromyographic data presented in these studies provides a needed empirical database for which future studies on pulling may be compared, particularly those data collected under actual working conditions.

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Contents

Chapter 1

Introduction

Evolutionary outcomes have allowed humans to interact with their environment through the use of a versatile manus. If a person is not locomoting within the environment, she or he is almost certainly performing determined manipulative activities. When considering basic form-function relationships, the phylogenetic development of the trunk, shoulder complex and upper limb of hominids was necessary to provide optimal versatility for engaging in manual materials handling activities. These developments allowed activities such as hunting and gathering to be performed with greater mechanical and physiological efficiency and were critical to the evolutionary success of homo sapiens. It is somewhat paradoxical that employment of these evolutionary adaptations to perform diverse, repetitive occupational activities seemingly has caused humans to suffer a variety of deleterious health effects.

In a micro-ergonomics approach, the operator-machine system can be viewed as the collection of one or more operators physically interacting with an object to achieve a desired outcome (McCormick and Sanders, 1982). Generally, an operator will manipulate an object by either lifting, lowering, carrying, pushing or pulling it (Snook *et al.*, 1978). From a biomechanical perspective, what distinguishes these types of manual materials handling activities is the direction of the resultant force vector acting through the centre of mass of the object. The principal force component of a lift, lower or carry will occur in the vertical direction. A push or pull force will have its largest force vector acting in the horizontal plane, although in both theory and practice, direction of the net vector for any of these manual materials handling activities may not be acting purely in this plane (Grieve and Pheasant, 1981; Baril-Gingras and Lortie, 1995). A mismatch between the demands of the manual materials handling task and the capabilities of the operator can result in any or all of the following: injury to the operator, less than desirable efficiency and poor product quality. Ergonomists strive to understand better those factors which impact upon the compatibility between task demands and operator capacity.

Physical Ergonomists often develop models to assist in describing and understanding the complexities of human-system interactions. These models can be used as a foundation to develop guidelines describing acceptable manual materials handling limits. Various epidemiological, biomechanical, physiological and psychophysical models have been developed to study the problem of operator-task compatibility (*e.g.* Ciriello and Snook, 1999; Davis and Stubbs, 1977a and b; Davis and Stubbs, 1978; NIOSH, 1981; Snook and Ciriello, 1991, Waters *et al.*, 1993).

Although these models have resulted in a more scientifically sound application of ergonomic principles (Ayoub, 1992), the high, and seemingly increasing, incidence of occupational-related injury still remains problematic and creates a tremendous economic burden for industry (Ciriello and Snook, 1999) and indeed society itself.

Generally, manual materials handling guidelines establish acceptable and safe limits for an operator performing a particular task within a reasonably defined environment. Nicholson (1989) defines "acceptable limits" as those an operator is willing to handle. In this respect, psychophysical models generally have been used to establish manual materials handling limits. He defines "safe limits" as those established through biomechanical or physiological criteria. These models attempt to establish what loads or task-related factors that would increase the probability of injury to the operator. Validation of biomechanical or physiologically-based models therefore infers an understanding of the magnitude of stress that biological tissues can withstand before failing or succumbing to fatigue. Unfortunately, the direct measurement of loads experienced by intact biological tissue is difficult, and variability in operator-related characteristics adds to the challenges of successfully implementing safe limit models.

Many of the published guidelines are limited to specific task descriptions or are restricted to specific operator postures, while most occupations require operators to perform relatively complex, coordinated movements. While well-controlled laboratory experimentation is often necessary to identify the effect of a given independent variable, guidelines derived under such rigid conditions may not have much predictive value regarding the general epidemiological nature of soft-tissue injuries (Buckle *et al.*, 1992) or the efficiency with which a task may be completed. Often guidelines established by different models, yet for similar manual materials handling activities, do not agree as to what loads are acceptable or safe (Ayoub, 1992; Buckle *et al.*, 1992; Dempsey, 1998; Kumar and Mital, 1992; Leamon, 1994; Nicholson, 1989; Shoaf *et al.*, 1997). These disagreements underscore the reality that there is still a high incidence of work-related injuries in spite of the proliferation of theoretical and applied research in ergonomics that is attempting to contribute to an improved working situation (Pope, 1998). Thus worksite realities often limit the utility and even the validity of much of the published manual materials handling standards. Those researchers attempting to establish valid safety and performance parameters should consider experimental methodologies that reflect movements typical of industrial settings, even if these are evaluated under laboratory conditions.

The success of any ergonomic intervention is ultimately assessed by its ability to minimize the musculoskeletal, physiological and psychological stresses and strains placed upon the operator, while optimizing the performed manual materials handling activities. The production of goods and the delivery of services, in many cases, require a worker to physically manipulate an object. Whether through administrative controls or ergogenic aids, much of the traditional heavy manual materials handling activities, such as lifting and carrying, has been eliminated in many industrial sectors (Resnick and Chaffin, 1996) and replaced with mechanical aids or else more preferred pulling and pushing actions (Koningsveld and van der Molen, 1997; Schibye *et al.*, 1997). Unfortunately, it is not always possible or practical to perform a manual materials handling task employing safe loads and optimal operator postures. Some tasks or occupations cannot be improved upon either due to engineering limitations, irresolvable workstation design flaws or financial barriers. Movements in the horizontal plane, such as pulling, are often preferred manual materials handling activities because these require less muscular effort than those done against gravity, such as lifting, lowering, and carrying (Kumar, 1995a).

Various studies have reported that approximately 20% of all overexertion injuries within manual materials handling activities are attributed to the execution of horizontally directed forces, such as pulling and pushing activities (NIOSH, 1981; Statistics Canada, 1991). Van der Beek *et al.* (1999) reported that pushing and pulling activities accounted for 15% of the accidents and overexertion injuries at building construction sites. These statistics are not surprising considering Baril-Gingras and Lortie (1995) found that nearly half of all manual materials handling activities executed in a warehouse setting were either pushing or pulling in nature. In this regard, establishment of guidelines for the design of workstations and the identification of potential mechanisms for injury associated with pulling activities should have both direct and indirect benefits to industry. Some have suggested that perhaps the frequency of push-pull related injuries are under-reported or improperly classified at the time of reporting because these activities are often associated with lifting or lowering activities and these are assumed, perhaps incorrectly, to be the likely causative factor of the injury (Kumar, 1994).

The predominance of pulling actions has been investigated for warehouse activities (Garg, 1986; Kuorinka *et al.*, 1994), service industries (Winkel, 1983; Garg *et al.*, 1988; Gite and Yadav, 1990; van der Beek and Frings-Dresen, 1994; Baril-Gingras and Lortie, 1995; de Looze *et al.*, 1995; Frings-Dresen *et al.*, 1995; Kumar, 1995b; van der Beek and Frings-Dresen, 1995; Lortie and Baril-Gingras, 1998), construction (van der Beek *et al.*, 1997; Paquet *et al.*, 1999) and the civil service (Gagnon *et al.*, 1987; Gledhill and Jamnik, 1992). Despite this extensive research record, little is known about the manner in which a pulling task is executed, in comparison to other manual materials handling tasks such as lifting and carrying.

While a "pull" can be generally defined as a displacement of a load in the direction of the person creating the effort, how the motive forces are generated by the operator can be quite complex and varied in nature. Hence, it is important to specify the type of pulling task to be examined. In the current study, pulling will be examined as an upright, standing and stationary activity with respect to the operator exerting the effort. In order to understand better this type of pull exertion, identification of those variables (*i.e.*, environmental, workstation, task and operator) that are specifically important to this type of pull task is required.

Many researchers have examined how workstation or operator-related factors influence the magnitude of maximal pulling forces. These factors include: the line of pull about various locations in the frontal plane (MacKinnon, 1998), the conditions at the shoe-to-floor interface (Dempster, 1958; Grieve and Pheasant, 1981; Lee *et al.*, 1992; Kerk *et al.*, 1994), the effect of various operator postures including sitting (de Looze *et al.*, 1995; Haslegrave *et al.*, 1997; Imrhan and Ayoub, 1990; Mital and Faard, 1990; MacKinnon, 1998) or having the feet or legs stabilised (Kroemer, 1974; Kumar, 1994; Kumar, 1995a; Kumar *et al.*, 1995), the execution of different pull directions in the sagittal plane (Garg *et al.*, 1988; Mital and Faard, 1990; Imrhan and Ramakrishnan, 1992), the orientation of the feet from the point of application of the pull force (Ayoub and McDaniel, 1974; MacKinnon, 2002) and sex-related differences (Ayoub and McDaniel, 1974; Chaffin *et al.*, 1983; Garg *et al.*, 1988; Fothergill *et al.*, 1992; Kumar, 1994; Kumar, 1995a; Kumar *et al.*, 1995; Mital *et al.*, 1995).

The most commonly studied parameter is undoubtedly the influence of pull height on maximal pull force. Researchers have employed experimental protocols which have examined heights relative to the morphology of the subjects (Ayoub and McDaniel, 1974; Kroemer, 1974; Davis and Stubbs, 1977b; Garg and Beller, 1990; Gite and Yadav, 1990; Daams, 1993) or heights that were relative to some absolute point in space (Warwick *et al.*, 1980; Grieve and Pheasant, 1981; Pheasant and Grieve, 1981; Chaffin *et al.*, 1983; Grieve, 1983; Gagnon *et al.*, 1987; Garg *et al.*, 1988; Lee *et al.*, 1989; Fothergill *et al.*, 1991; Lee *et al.*, 1991; Fothergill *et al.*, 1992; Lee *et al.*, 1992; Kumar, 1994; Kumar, 1995a; Kumar *et al.*, 1995; MacKinnon, 1998).

All the aforementioned studies used either isometric, isokinetic or isoinertial models to examine the maximal pull forces. As Mital and Kumar (1998) have identified, all these modes of strength testing have their advantages and disadvantages. Unfortunately, the diversity in experimental methodologies of these studies, which create large differences in the reported pull force values, has made it difficult for direct comparisons to be made and for more robust and practical guidelines to be established.

Few studies have incorporated dynamic, kinematic evaluations to examine the events that culminate in the execution of a manual materials handling activity, such as pulling. The absence of kinematic data as an input parameter is a limiting factor when attempting to select the appropriate guidelines to implement within a working environment. This might perhaps explain why after more than two decades of ergonomics research in this area there still remains a high incidence of musculoskeletal injuries related to manual materials handling (Hoozemans *et al.*, 1998 and 2002).

Previous research on pulling tasks has attempted to examine an activity simply based on the success of one outcome parameter, such as the ability to create maximal pull forces. Yet a clear understanding of how an operator performs the task cycle is clouded when an event is reduced to one or two summary values. It is far more important that those biophysical, physiological and psychological events that influence the outcome of a task are considered (Charteris *et al.*, 1976). A task that is too strenuous may result in a poor performance, contribute to the early onset of muscular fatigue and increase the potential for both acute and chronic injuries.

It seems that *in situ*, repetitive pulling actions are more common than the need to produce maximal pull forces. It could be assumed that the operator would intuitively adopt movement patterns that either reduce stresses on the body, or minimise the mechanical or physiological effort required, or both (van der Beek *et al.*, 1999). From a coordination perspective, the operator has an infinite number of ways in which to complete the task. For example, there are several human morphological characteristics that could influence how a person might choose to execute a pulling action. Employing the definition of a pull, one expects that the hand will move in a sagittal plane at a defined horizontal level, away from the initial point of application of the force. As most of the body's mass is contained within the trunk region (Chandler *et al.*, 1975), exploiting the inertial properties of the trunk can aid in the acceleration of the hand and thus the load. Although this strategy could reduce the metabolic energy requirements or increase the magnitude of the applied force, it could also increase the potential for injury. Acceleration of the hand as a result of the kinetic link to the trunk may occur by several means. The trunk can extend away from the position at which the load is located, or the trunk can rotate about its longitudinal axis, or a combination of these movements may occur. Considering evidence from the lifting literature (Ladin *et al.*, 1989; MacKinnon and Li, 1998), it could be predicted that these movement strategies would have varying impacts upon the magnitude of the reaction forces at various joints and the kinematics of the load. These inertial strategies should also minimise the demands on the gracile muscles of the distal aspect of the arm.

Imrhan and Ayoub (1990) proposed that future ergonomics-related research should focus less on predictive kinetic models and more on the importance of the kinematic characteristics of the activity. They suggested that kinematic data are equally important as kinetic profiles when forming explanatory models of underlying biomechanical processes. As in the lifting literature, the guidelines from numerous research studies on pulling activities has yet to provide a standard known to eliminate or reduce the incidence of musculoskeletal injury. Insight into common coordination strategies should lead to a better understanding of those pulling activities that predispose a person to injury and/or influence the ability to coordinate the production of the required forces.

Workstation constraints, such as load magnitude and location of the application of the force, will affect the manner in which a pulling task is completed. It becomes important to understand the changes in neuromuscular recruitment and segment motions with changes in task demands. With this information, the Ergonomist can identify movement patterns that might influence the successful completion of the pulling task and assist in identifying musculoskeletal injury mechanisms. As Imrhan and Ayoub (1990) reported, there may also be distinct movement patterns consistent across pulling actions even though the workstation conditions change. This might provide some evidence that manual materials handling activities, such as pulling, are not solely learned from repetition, but emerge from pre-existing schemas of movement (Lee, 1995).

Ayoub (1992) correctly stated that in order to design an efficient manual materials handling system all the components that impact on the ability of the operator to adapt must be clearly understood by the Ergonomist. The design of a perfect manual materials handling system can only be accomplished when all the cause and effect relationships become known. Conceptually, identifying and understanding the biomechanical and physiological parameters is the first step to eliminating the harmful demands on the operator and improving task efficiency.

The association between the demands of an external load and the stresses experienced by the musculoskeletal system are difficult to quantify. This relationship will never be clearly understood until such time that technological advancements allow for the direct measurement of muscle-tendon and skeletal systems. However, external task demands and workstation designs can be experimentally manipulated, while indirect metrics of internal loading, such as muscle electromyography, joint kinematics and subject perception, are assessed. This is a well accepted methodological approach in the cognate areas of biomechanics and ergonomics and will be employed in a series of experiments that will constitute this dissertation.

For the majority of the workday, operators are required to perform submaximal, repetitive exertions as part of the job demands. While there has been some empirical data reported on back kinematics for *in situ* lifting tasks and occupations (Marras *et al.*, 1995; Norman *et al.*, 1998), similar quantitative evidence for industrial demands related to pulling exertions is lacking. This absence of information can be partly attributed to the difficulties of measuring external pulling kinetics upon an operator and, perhaps, to the focused attention given by researchers to lifting activities. Technological improvements and a growing interest in the relationship between pulling and low back and shoulder complaints will likely contribute to a growth of research in this area. As a start, a laboratory-based approach should be considered to assess how a person exerts a pull exertion. A better understanding of the kinesiology of this movement pattern will provide a platform to derive work guidelines, identify pathomechanisms and improve workstation design, among other critical issues. Once researchers have derived benchmark data in the laboratory, then comparison to kinesiological data obtained *in situ* can be undertaken and methodological approaches to studying occupations employing pulling exertions derived.

The purpose of this research is to gain a better understanding of how humans perform a pulling force. Identifying how the operator responds to different submaximal loads and various workstation constraints could provide some insight into factors that reduce the efficiency of a pulling action. Although the relationships between pulling activities and musculoskeletal disorders, other than low back pain, have not been extensively studied (Hoozemans *et al.*, 1998), there is growing evidence that neck, shoulder and elbow disorders may be posture-related during pulling activities (Hoozemans *et al.*, 2002). By varying the environmental constraints, observed differences in coordination strategies may provide some information on what movement patterns may be potential precursors to injury and accidents. Specifically, the following experiments will be carried out in order to systematically derive methodologies and collect empirical information regarding the execution of a single-handed, submaximal, upright pulling exertion.

A. Experiment 1 will explore the effect of various operator postures and pull locations on the expression of maximal isometric strength. These data should provide information about typical reach envelopes and which operator postures are best suited for creating maximum isometric forces.

B. Experiment 2 will employ a psychophysical approach to assess acceptable load and pull frequencies associated with idealised operator postures. Describing these workload factors could provide a basis for establishing methodologies suitable for examining submaximal exertions.

C. Experiment 3 will assess the effects of foot position on the manner of execution and level of repeatability of submaximal pull forces. While fixing the feet could impose undesirable limitations upon how an operator might effect a pull movement, this experimental control is necessary to understand better the systematic changes in the function of other aspects of the anatomy, particularly that of the trunk.

D. Experiment 4 will employ a biomechanical approach to examine how a change in pull locations might influence how an operator exerts a submaximal pull force. Trunk kinematics and electromyographical activities of selected trunk and shoulder complex muscles will be assessed for changes in function as the location of the pull force is altered about various locations in the frontal plane. The influence of load magnitude about these different pull origins will also be considered.

E. Experiment 5 will employ a similar methodological approach to Experiment 4 although the load magnitude and pull location will remain fixed while the distance the operator is located from the frontal plane containing the origin of the pull will be altered. Thus, the influence of the magnitude of a forward reach will be assessed.

Experiments 1 through 3 will attempt to resolve several methodological issues, including loading profiles and the impact that subject morphology might have upon task execution. Very little information exists regarding the standardization of pull exertions for experimental purposes. Experiments 4 and 5 will be used to examine one-handed, upright pull-exertions within a workstation simulating common physical constraints placed upon the operator. These results should provide a greater insight into how a person might create a horizontal pull force while assuming awkward postures.

Development of methodological approaches to better understanding task execution strategies will certainly expand upon the existing body of knowledge regarding upper body pulling exertions. Insight into how a person performs an upright, single-handed pulling task will provide direction for developing manual materials handling guidelines which are paramount to Ergonomists attempting to design suitable workstations and work practices (Brewer and Hsiang, 2002). The five experiments have been written up separately and constitute chapters 3 through 8 in the thesis.

Chapter 2

Review of Literature

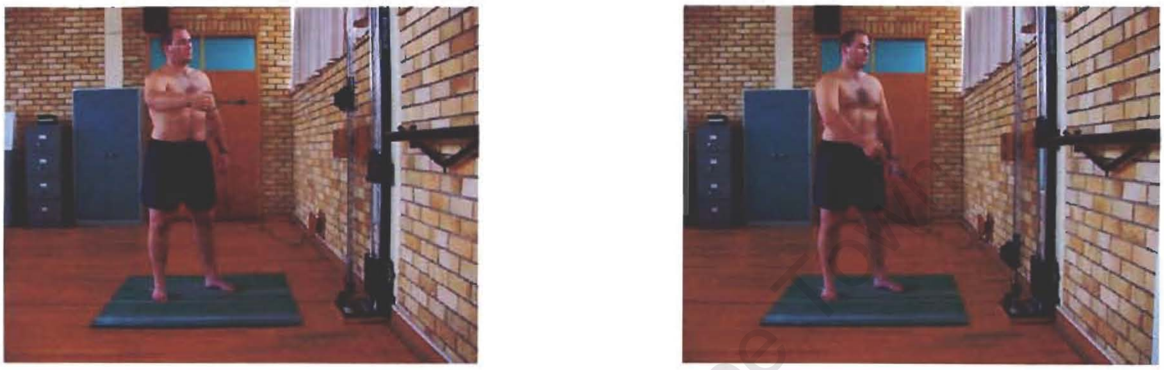
2.1 Introduction

The available ergonomics literature examining pulling activities is not as large as that of other manual materials handling activities. Significant amounts of research resources have been directed towards lifting, lowering and carrying activities, as historically these have been considered to be the primary aetiological factors in operator musculoskeletal pain and discomfort. However, in order to reduce the net mechanical loading experienced by an operator, lifting, lowering and carrying tasks are being systematically eliminated in favour of pushing and pulling tasks (Schibye *et al.*, 1997; Frings-Dresen *et al.*, 2000)).

Past research into pulling activities has focused primarily on workstation and equipment design factors and their effects on maximal pulling actions. While this focus is important in a workstation design context, it has not adequately served Ergonomists in identifying safe pulling practices, provided much insight into those factors which contribute to acute and chronic soft tissue injuries (van der Beek *et al.*, 2000), or identified movement strategies an operator might adopt to execute the task.

The literature contains many different operational definitions of pulling. In the context of this study, pulling is the exertion of a force, by the hand, in which the direction of the resultant force vector is parallel to the ground, located in a defined sagittal plane and directed towards the frontal plane containing the subject (see Figure 2.1(a)). However, others consider a force to be a pull when the largest force vector is directed towards the operator (see Figure 2.1(b)) (Hoozemans *et al.*, 1998). While the latter definition may seem to have greater operational validity, depending upon the orientation of the torso at the time of exertion, this definition could also be considered a lifting task. In this respect, the former definition seems more desirable when attempting to examine the execution of pulling exertions under laboratory conditions. The lack of a conventional definition of a pull force and how a pulling motion is operationalised in an experimental context has made it difficult to compare existing results from the literature.

Past research has examined two genres of pulling tasks. While the definition of a pull typically refers to the direction of the forces creating a change in momentum of the object acted upon, it does not delineate how these forces may be created. The first researched form is a 'cart' type pull (see Figure 2.2(a)). The load is typically on wheels and the operator uses the whole body to execute an action against the resistance. In this type of pulling activity, the upper body remains relatively static, while the lower body provides the majority of the motive forces. Snook and colleagues (*e.g.* Snook and Ciriello, 1991) at the Liberty Mutual lab have probably contributed the most to developing work practice guidelines for cart type pulls, while others have examined this type of pulling activity both in laboratory (Andres and Chaffin, 1991; Lee *et al.*, 1991; Lee *et al.*, 1992; de Looze *et al.*, 2000) and industrial settings (Winkel, 1983; de Looze *et al.*, 1995; Frings-Dresen *et al.*, 1995; van der Beek and Frings-Dresen, 1995; van der Beek *et al.*, 2000).



(a) (b)

Figure 2.1: Examples of how pull motions are operationalised either as a horizontal pull (a) or a pull directed towards operator (b).

(a) (b)

Figure 2.2: Cart type pulling motions (a) and fixed workstation pulling actions (b).

The second type of pulling task commonly examined is typical of fixed workstation activities (Warwick *et al.*, 1980; Chaffin *et al.*, 1983; Daams, 1993; Kumar, 1995a; MacKinnon, 1998). In this type of pulling activity, the lower body is fixed and reasonably stationary and the upper body musculature is mostly responsible for displacing the load (see Figure 2.2(b)). While no robust guidelines have been developed for this type of pull exertion, the literature has provided some insight into the aetiological factors of manual materials handling-related injuries to the back, neck, shoulder and elbow joints (Hoozemans *et al.*, 1998).

This study will utilise a model of the second type of pulling action, where the feet are in a relatively stationary position on the ground and the muscles of the upper body effect changes to the momentum of the load. While it is important to review all studies on pulling activities, the main focus of this chapter, when possible, will be to examine those research studies which have employed a similar type of pulling posture as will be used in this work.

The primary purpose of most pulling research has been the quantification of maximal operator forces and how various subject, task and environment- related factors influence these maximal values. These data have provided some basis for identifying undesirable task demands and some insight into the forces and moments imposed upon various parts of the operator's body. Submaximal, repetitive pulling activities have also been studied to a limited extent, but these data are normally presented in the context of specific occupational tasks and are measured in a relatively uncontrolled, *in situ* environment. The following sections will examine the impact of pertinent operator-machine interface factors on pull exertion performance.

The following literature review will focus on three main areas of research related to pulling exertions as a manual materials handling task. The first part of the review of literature will explore those operator- and workstation-related factors that influence the performance of a pull exertion. The second aspect of the review will examine those studies that have employed biomechanical and electromyographical approaches to understand better the demands upon an operator while executing pull exertions. Finally, an examination of epidemiological-based research, exploring the relationship between occupations employing pulling exertions and operator injury, will be conducted.

2.2 Operator-Related Factors

Many studies have demonstrated that the physical attributes of a subject have a direct influence on the magnitude of the pull forces. It is hypothesised that when presented with a task, an operator will consider a variety of postures to either maximise strength or minimise discomfort (Pinder *et al.*, 1995). A better understanding of operator-related variables, particularly those that relate to pulling posture, should provide some insight into the future design of workstations, particularly those workspaces where pulls from diverse or awkward origins are required.

Sex-Related Effects

In recent years, many countries have introduced equal opportunities employment legislation. An outcome of this process is that in many industrial settings males and females may be required to perform the same task under the same conditions. In this respect, companies should re-examine task descriptions and demands to ensure that work practices do not contradict existing occupational health policies, which were developed when workforces were more homogeneous in morphological composition (van der Beek *et al.*, 2000).

Often it is not possible to make generalisations regarding the differences in strength performances between male and female subjects employed as research subjects. The absolute difference between the force producing capabilities of the sexes is highly dependent on the demands of the protocol and the degree of freedom to choose the movement strategies possible to complete the task (Ruhmann and Schmidtke, 1989).

In many situations in which maximal or near-maximal efforts are required, females are at a disadvantage as they typically have less muscle mass and are smaller in stature than males. It is well known that the average male will be stronger in absolute terms than the average female. Employing a postural stability diagram (PSD), Pheasant and Grieve (1981) found that females exerted less pulling force in all directions when compared to men. Employing a female to male ratio comparison (expressed as a percentage of body mass), they found that the pulling strengths of females were on average 88% of males. Fuster *et al.* (1998) found that the average pull strength of a group of university females was 53% less than those of male cohorts. Employing principal components analysis they indicated that static measures of strength, including pulling strength, were most dependent on body size measures, such as stature and mass. In a similar context, Ayoub and McDaniel (1974) found that subjects with higher masses had an advantage in creating a pull force.

Female operators are often disadvantaged by smaller segment lengths, and as a consequence smaller reach envelopes, in comparison to males. Pulling exertions may need to be attempted at large absolute distances from the operator's centre of mass. For the smaller operator, these demands may require the adoption of an unstable base of support, such as a large forward flexion at the trunk or shifting the majority of the mass over one foot, in order to attempt the exertion. These undesirable postures may not only affect pulling performance but also compromise the stability of the operator.

Fothergill *et al.* (1992) compared maximal horizontal isometric pulling forces over a series of different handle heights and types. They found that when combining all experimental conditions, the ratio between female and male relative strength (as a function of body mass) was 0.80 (range of 0.78

to 0.91) and was dependent on handle type. In absolute terms, the ratio was 0.72. These findings suggest that for workstations that are exclusively operated by females, some handle types and heights may be more desirable for producing forces.

Chaffin *et al.* (1983) examined maximal two-handed isometric pulls at different handle heights. At three heights (670, 1090 and 1520mm) female strength was significantly lower than males by 52.4, 33.7 and 17.8% respectively. It appears that the differences due to sex seem to decrease as handle heights are increased above the abdominal/thoracic region of the subject, revealing how a poorly designed workstation can increase the demands of a task regardless of the physical attributes of the operator.

Ayoub and McDaniel (1974) found that two-handed isometric pulling force was maximised when the bar height was set at 30% of standing reach height (RH) for males compared to 40% RH for females. These differences are difficult to explain, considering that the average centre of mass location for a female tends to be relatively lower, albeit minimally in absolute terms, than that of males.

Kumar (1995a) examined two-handed maximal isometric and isokinetic pull forces at three handle heights (350, 1000 and 1500mm). On average, the males were 13, 32 and 43% stronger during the isometric conditions and 32, 35, and 45% stronger in the isokinetic conditions compared to the females at the same three heights. A later study (Kumar *et al.*, 1995) appears to repeat the earlier study except with twice the sample size of the original study and the lower handle height was increased to 500mm from 350mm. For the 500, 1000 and 1500mm handle heights, the males were 27.7, 28.3 and 21.5% stronger during the isometric conditions and 38.0, 32.7, and 35.1% stronger in the isokinetic conditions compared to the females at the three respective heights. The values from the second study seem to be less variable (i.e. approximately 30% difference in male and female strength) compared to the first study, which probably reflects the improved sampling stability that comes with increased sample size, or perhaps the selection of more suitable pull heights. The trend of decreasing sex-related strength difference with increasing handle heights noted in the Chaffin *et al.* (1983) study does not appear to be replicated in these studies. In fact, the opposite trends were observed in the isometric conditions of the Kumar (1995a) study. It is interesting that had either researcher attempted to derive workstation guidelines from these data, very different recommendations would have been put forth. This further emphasizes the need to carefully assess *a priori* the impact of experimental control in future studies on pulling activities. The variability associated with different heights of exertion is considered later in this chapter.

Van der Beek et al. (2000) examined male-female differences in exerted forces and physiological load during pulling of wheeled cages, by experienced Dutch postal workers, under simulated laboratory conditions. Initial analyses concluded that there were statistical differences due to gender in all dependent measures, which included average, initial and ending pull forces, oxygen uptake and heart rate. However, when these data were corrected for personal factors, such as mass, stature and maximum capacity, only the average and ending pull forces remained significantly different. This suggests that factors other than operator morphology accounts for these differences and could include working technique, personal motivation and job experience. These authors suggested that men and women adopt slightly different working techniques under these experimental conditions.

The realities of sexual dimorphism, as well as the fact that humans are not simply scaled anthropometric versions of each other, has always posed methodological problems in ergonomics research. Whether to employ relative or absolute independent variables for such factors as load manipulated or height of pull will influence the outcome effects of these variables. If the independent variables (e.g. handle height) dictated by the protocol are established in relative terms (e.g. % of stature), then true absolute difference due to sex might be masked. If the independent variables are established in absolute terms, then inclusion of both male and female subjects in an experimental sample may alter or obscure trends in the data. In either case, it remains difficult to design studies to determine robust manual materials handling guidelines suitable for all potential operator morphologies and seemingly, levels of experience.

The ability to produce sufficient magnitudes of strength, while coping with the effects of neuromuscular fatigue, will have a tremendous impact upon an operator's risk for injury. Typically, guidelines should be established so that a majority of the female workforce can safely cope with the manual materials handling activity (NIOSH, 1981). This strategy is assumed to reduce the risk of injury and from a statistical perspective is less discriminatory to female employees. Unfortunately, these guidelines are often established under reasonably ideal laboratory conditions and their efficacy *in situ* is more often assumed rather than experimentally tested.

One- Versus Two-Handed and Dominant Versus Non-dominant Pull Exertions

When faced with a task that requires a pull force, the operator may choose to grasp an object using one or two hands. This decision may be affected by the absolute strength of the operator, the magnitude of the force demands, the opportunity to grasp the load or the postural restrictions imposed by a workstation's design.

One-handed exertions are weaker than two-handed and typically involve asymmetrical postures (Fothergill *et al.*, 1991). Chaffin *et al.* (1983) compared one- versus two-handed pulls and found that one-arm pull strengths averaged approximately 73% of the two-armed values. This would indicate that pull strengths are not solely dependent upon arm strength (as the reduction in strength during one-armed trials would have been closer to 50% of the two-handed pulls) but depend on inertial, motor control and motivational factors as well.

MacKinnon (1998) compared the isometric pull strengths of left and right hands about various locations in the frontal plane and under various postures. He found no statistically significant differences in the values obtained between either hand, although in most cases the subject's dominant hand often had slightly larger values. This can probably be attributed to slight coordination effects rather than contralateral strength differences.

Warwick et al. (1980) also examined isometric strengths for left, right and both hands while subjects exerted pulls. While they published the results in tabular format, they did not perform any statistical analyses upon these data. Although the two-handed pulls seemed to be larger than either single-handed exertions, there appears to be no difference in the pull force magnitudes between the left and right hands.

More research is required to determine the benefits and liabilities of one- versus two-handed pulls. Two-handed pulls are advantageous in that the load can be shared amongst more of the anatomy and this probably forces the operator to adopt a relatively symmetrical posture. However, one-handed pull exertions may be more common to upright pulling tasks. While one-handed pulls allow the operator to create forces towards the extremes of the reach envelope, it is likely that this will require asymmetrical postures and greater ranges of motion of the upper body. Loading an asymmetrical posture will undoubtedly create higher demands upon the musculoskeletal system, in a situation when an operator is not able to optimize his or her ability to produce force (MacKinnon, 1998). Perhaps employing a bracing technique using the free hand can minimize these potential negative effects, although there has been little research investigating the advantages of this strategy in standing pulling exertions.

Foot Positioning

The manner in which an operator positions the feet to execute a pull in a workstation has been shown to not only have an effect on the expression of strength, but is also related to the safety of an operator (Grieve, 1983). It is important that the foot/floor interface is optimal so that the force couple allows the operator to function in a safe and efficient manner when executing a pull. From a methodological perspective, this issue can be studied from two approaches: allow a subject to freely choose how the feet will be positioned during a pull or initiate experimental controls and standardise the foot positions.

Ayoub and McDaniel (1974) suggested that the foot positions were critical for biomechanical efficiency of two-handed pull forces. They reported that asymmetrical foot positions, with one foot in a more forward position, allowed for the generation of the greatest maximal isometric pull forces. In fact, when the foot went beyond the parafrontal plane by 10% of standing reach height, the pull force was further increased. Pheasant *et al.* (1982) found that strength exertions were improved when subjects were allowed to adopt 'freestyle' foot postures compared to experimentally controlled foot postures during two-handed pulls. It should be noted that these studies examined two-handed exertions and whether postures and foot positions of two-handed pulls are similar to those adopted to maximise performance in one-handed pulls cannot be assumed.

Warwick *et al.* (1980) employed an experimental procedure that fixed the foot positions in an absolute manner relative to the origin of pull. While no statistical analyses were reported, the data suggested that there were differences in the magnitude of maximal pull forces reported for a series of left, right and two-handed pulls for five conditions of various foot orientations. It should be noted that the prescribed foot positions in this protocol were extreme (in this author's opinion), necessitating large rotations of the trunk about its longitudinal axis. These postures are indeed awkward (Haslegrave *et al.*, 1997) and likely would not be typical of a regular, repeated task.

Both Daams (1993) and MacKinnon (1998) compared the effects of fixed versus free foot positions on the magnitudes of maximal isometric forces produced during one-handed pulls and found that a fixed versus free foot posture reduced the efforts by amounts of approximately 50 and 36% respectively. It must be acknowledged that advocating free postures makes comparison of future studies in this area difficult by creating methodological replication problems. Pragmatically, future studies that employ self-selected foot postures should assess how these relate to a subject's morphological and strength attributes. These personal factors must be related to a subject's ability to maximize force production and/or minimize risk of injury. It is likely that methodologies employing subject-selected foot postures reflect better the kinematic and kinetic profiles typical of an operator *in situ*, but findings are limited with respect to their generalizability.

In contrast to the two previous studies, Chaffin *et al.* (1983) found no strength differences for conditions of varying levels of self-selected foot placements during pulling activities, suggesting that either several whole-body postural combinations, advantageous to the expression of pulling strength, exist or foot positions play a minor role in performing pull exertions. These findings provide support to introducing some level of experimental control of subject foot positions within an experiment assessing varying conditions of pull exertions.

The number of research studies on pulling which examine the effects of foot position on force production leads to some interesting questions regarding the direction of future experimental protocols. While it may be necessary to control certain independent variables in order to make intra-subject, inter-subject or inter-study comparisons, it may be argued that the predictive validity of these findings is limited when estimating outcomes in industrial settings and thus, the use of relatively "free" postures should be promoted in future experimental protocols (Grieve and Pheasant, 1981; Daams, 1993; Haslegrave *et al.*, 1997). Warwick *et al.* (1980) support a counter-argument that advocates strict control of body postures, including foot placements. Subsequent results can then be manipulated using a modelling approach to estimate *in situ* postures and demands.

MacKinnon (2002) examined the effects of foot positions upon load kinematics under submaximal isoinertial pulling conditions. Based on a set of normative data, he first described foot orientations for subjects performing a simple pulling task. In a second part to the experiment, he compared the kinematic histories of the load and foot orientations when an isoinertial pull force was exerted while the subject assumed average and freely-chosen foot postures. No statistically significant differences in these variables were found. It should be noted that no extreme pull origins were considered in this study. In spite of this experimental limitation, while fixing foot positions when examining a pulling exertion must be recognized as a methodological limitation and likely a departure from how operators function within a workstation, these results support the adoption of some level of experimental control often needed to allow researchers to perform comparisons within a repeated-measures experimental design.

As the pulling motion becomes more complex from a kinematic perspective, so too will the strategies employed by the operator. The greater the displacement of the load, the more likely the operator will alter the foot orientations during the execution of the movement. Foot movement will have an impact on force execution as well as a potential for slips and loss of balance. As reported in the lifting research (Delisle *et al.*, 1999), the analyses of dynamic footstep strategies will take on greater importance when trying to understand the execution of pull forces. To date, no known studies have examined foot movement-time histories for pulling tasks.

Occupational safety-based research has examined the relationship between pull execution and the potential for operator slips and falls. The incidences of operator injury due to acute slips and falls during pulling are quite significant. Movement between the shoe and floor (*i.e.* a slip) will occur when the ratio of tangential to normal forces exceeds that required to overcome the limiting coefficient of static friction (Grieve, 1983). Manual exertion in any direction, other than the pure vertical direction, has the potential to make the operator slip, particularly when maximal forces are exerted. Grieve (1983) indicated that those who had a high strength to mass ratio were the most likely to slip when performing manual exertions. As the pull force vector is directed above the operator's centre of mass, the risk of slipping further increases. This would put shorter operators at a disadvantage in workspaces that have fixed pull height locations.

Lee *et al.* (1992) examined a series of handle heights and concurrent coefficient of friction (COF) under foot while a subject pulled on a customised cart simulator. They found that as the handle height increased the COF increased, thus decreasing slip potential. However, it is noteworthy that the opposite trends were found during pushing, which would make the design of a cart for use in industry much more challenging, as often a cart will be both pushed and pulled during regular use.

In a fixed workstation, Ayoub and McDaniel (1974) indicated that given a choice, a subject would advance the lead foot past the frontal plane in which the origin of the pull is located. Athropometrically, this will lower the operator's centre of mass, and most likely increase the horizontal component of the net pull force vector. Kinetically, this will decrease the magnitude of the normal component at the foot and increase the tangential component. This posture would increase slip potential, especially if the COF between the foot and floor was small. If all attempts are not made to limit the required magnitude of pull force, whether isometric or dynamic, which has to be produced by an operator in a workstation, operators may have to adopt foot postures which gain mechanical advantages at the expense of safety (i.e. slip conditions).

Direction of Pull Force

Operators *in situ* engage in their occupational activities without hindrance of the methodological controls demanded of experimental research. They will normally choose to perform an activity to the best of their ability, with reasonable levels of efficiency and safety throughout the performance. In lifting and carrying activities, the direction of the load vector is considered to act in the plane of gravity. However, in pushing and pulling activities, the applied force cannot always be assumed to act in a purely horizontal direction (Fothergill *et al.*, 1993). Many studies of pulling activities make assumptions about the direction of the net force vector. Unless employing some methodological means to control the direction of the line of the pull (Kumar, 1995a; Kumar *et al.*, 1995), it cannot always be assumed that the net force vector acts solely in a horizontal plane bisecting a sagittal plane.

In an attempt to understand how an operator might choose to execute manual materials handling exertions, Grieve and colleagues examined the vector components of the resultant maximal forces exerted by an operator under various postural and environmental constraints (Grieve, 1979a; Grieve, 1979b; Grieve and Pheasant, 1981; Pheasant and Grieve, 1981; Pheasant *et al.*, 1982; Fothergill *et al.*, 1991; Fothergill *et al.*, 1992). By employing multi-directional force transducers and a data representation technique called a postural stability diagram (PSD), these researchers identified that a subject will often maximise forces in a desirable direction by exploiting the coupling effect of deviated forces. Not surprisingly, magnitudes of pull forces were found to be a function of the angle of exertion (Pheasant and Grieve, 1981). Whilst maximising the magnitude of a pull force has many obvious benefits, the concomitant deviant force vectors may ultimately be responsible for slipping and sliding by the operator or causing unintentional equipment damage. In theory, the PSD approach could be used to assess the effects of both subject and workstation-related constraints on the effectiveness of a task's design. However, since this employs a static analysis, its application to more dynamic *in situ* activities is limited. Future studies examining pulling activities as per its conventional definition should ensure that the line of pull is located in defined horizontal and sagittal planes.

Pinder *et al.* (1995) extended the PSD methodology to examine manual materials handling from a three-dimensional perspective, including the lateral forces created during one-handed exertions, which could not be determined from the original PSD model. They concluded that a significant lateral vector, one outside of the sagittal plane, exists when operators attempt to maximise the exertion. They too considered this to mean that it may be necessary for an operator to adopt a posture which not only increases the force exertion, but also the magnitude of deviant vectors away from the desired direction of progression.

De Looze *et al.* (2000) examined the vector direction of pull forces applied on a cart handle within a sagittal plane. Amongst a variety of handle heights (expressed as a percentage of shoulder height) and load conditions (expressed as a percentage of body mass) they found that the resultant "pull force vector" generally deviates from a pure horizontal plane. Amongst all the experimental conditions they found the angle to deviate from the horizontal as much as 14 degrees upwards to 6 degrees downwards during a cart pulling activity. This deviation from the horizontal (approximately 20 degrees in total) should not be taken to represent an absolute range, simply because independent variables such as handle height and posture would have an impact on these values. The anthropometric characteristics of the operator would also impact on these values, particularly if the methodological approach is to use absolute versus relative heights and loads.

While there exist no specific values for how much an operator may alter the resultant pull force vector from the intended direction of pull, either *in situ* or under uncontrolled experimental conditions, the fact remains that this outcome cannot be ignored. Firstly, biomechanical models that require hand force inputs must be accurate in the direction component of the vector, otherwise calculated resultant joint forces and moments along the kinetic link would be incorrect. Secondly, ergonomists should consider that the deviated component from the horizontal is most likely related to those circumstances when an operator might slip or fall. If so, the workstation design should account for this possibility and not place important controls or dangerous obstacles upon which an operator might stumble (Grieve, 1983). Knowledge of how an operator creates these types of manual materials handling forces will reduce the number of assumptions an ergonomist must make when analysing the operator-machine interface (Kerk *et al.*, 1994).

If pull forces are higher when the operator is not restricted to pure horizontal plane exertions, then this fact can be exploited in the manufacture of tools or workstation design. For example, Garg and Beller (1990) found that the largest dynamic pull forces were generated when a subject pulled at an angle of approximately 25 degrees from the horizontal. If petrol powered motors, such as those found in lawnmowers, were designed in such a manner, overexertion injuries might be reduced in high speed pulling tasks.

Imrhan and Ramakrishnan (1992) also examined how the direction of pull affected maximum isokinetic strength. They found that pull strength was maximised when the pull was towards the body rather than across the body. Future workstation design strategies should consider initiating the pull in a sagittal plane near the mid-line of the body, rather than from a plane at an angle to the main sagittal plane. This design strategy was also supported by Mital and Faard (1990).

Defining the direction of the pull force vector is an important consideration within the context of an experimental design. While most of the findings to date suggest that pulls towards the body are most effective in producing maximal force, a considerable amount of out-of-plane forces are still created by the subject, presumably to either stabilize the subject or due to workstation constraints. Furthermore, as the posture of the operator changes, for example if trunk flexion increases, pulls towards the body can be just as easily defined as lifting activities, as the direction of the resultant force vector approaches a vertical orientation. Perhaps investigations of submaximal, repetitive movements should consider employing a definitional approach to examine pull exertions. For investigations of submaximal exertions, issues of interest are not necessarily limited to force production capacity but to assess movement strategy and coordination. Defining the pull exertions with respect to a horizontal and a sagittal plane simplifies the model and creates better control of the dynamics of the human-machine system. This methodological approach should allow for a better understanding of how the manipulations of subject- and task-related variables influence outcome dependent measures.

2.3 Task-Related Factors

Deriving guidelines that delineate both maximal allowable limits and desirable submaximal workloads for pulling exertions with respect to task- or workstation-related factors would be of tremendous value to ergonomists and industrial engineers. The literature is lacking a comprehensive statistical meta-analysis of existing data on operator capacity and the influence of task-related variables upon these values. Finding consensus within the existing literature to derive guidelines that could assist in describing safe pulling activities is difficult, simply because of the huge diversity of experimental protocols that makes seemingly related literature of a very specific task difficult to compare. An incomplete description of any mechanical or task-related variables that require muscular effort and physiological demands upon the operator will result in a flawed estimation of the soundness of the protective guidelines (Westgaard and Winkel, 1996).

Some of these pertinent independent experimental factors include: cartesian location of the origin of the pull; load resistance (isometric, isokinetic, isoinertial, dynamic); and postural constraints due to the workstation (limited foot space, standing versus sitting). Kumar *et al.* (1995) suggested that a failure to account for such factors could produce errors in the region of 60% when comparing published values.

Location of Origin of Pull Force

The point of origin of the pull force (where the operator grasps a handle or object) is probably the most important factor influencing the maximum forces the operator will be able to produce (Fothergill *et al.*, 1992) and the movement strategies an operator will employ to complete the task.

A comparison of published maximal pulling force values is graphically represented in Figure 2.3. Of the number of papers reviewed in this chapter, it was only possible to compare three (Chaffin *et al.* 1983; Daams, 1993; MacKinnon, 1998) because these studies employed reasonably similar protocols. Figure 2.3 reflects one-handed isometric pulling forces at fixed handle heights, generated while subjects adopted a relatively "free" posture. These data are for combined male and female efforts as reported in the original sources. These data suggest that as handle height increases (beginning with a minimum value of 500mm) above the supporting surface, the magnitude of the isometric pulling force decreases. A Pearson Product Moment Correlation calculated for these mean data reveals a correlation coefficient of -0.65, suggesting that less than half of the variance in force production can be explained by handle height.

Normalizing these data to body mass and stature strengthens the degree of association (r = -0.85) between these variables (see Figure 2.4). While the development and promotion of allowable limits guidelines might be best expressed in absolute magnitudes, perhaps relative terms should be considered in future experimental designs until a better understanding of the associations between operator morphology, task execution strategies and workstation constraints is gained.

It is difficult to find data from similar protocols for between-study comparisons of two-handed pulls. The data from two studies from the University of Alberta (Kumar, 1995a; Kumar *et al.* 1995) are presented in Table 2.1. Table 2.1 indicates that of the two handle heights tested, the higher height had smaller pull force values. These findings seem consistent for those of single-handed pull exertions. Data from two-handed pull exertions also indicate that females were at a disadvantage when creating maximal pull force exertions, because the female values were consistently lower than the males. These findings further support the disadvantages females will encounter in workspaces designed with fixed handle heights because of their smaller morphologies compared to males. It is noteworthy that although the protocols were virtually identical for these two studies, extremely large differences in pull force values were reported. High repeatability of maximal isometric forces and moments of forces have been reported in the literature for isolated joints (Abernethy *et al.*, 1995; Behm and St. Pierre, 1997), but variability would expectedly be higher in a movement such as pulling, due to the increased number of articulations and segments involved in producing the isometric force (Warwick *et al.*, 1980). However, it is difficult to attribute these inter-study differences to either methodological factors or actual subject strength differences.

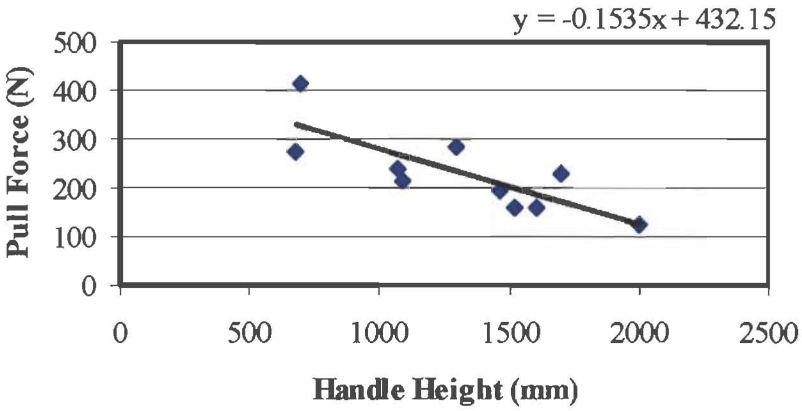


Figure 2.3: One-handed isometric pulling forces versus handle height (Data taken from Chaffin *et al.* 1983; Daams, 1993; MacKinnon, 1998).

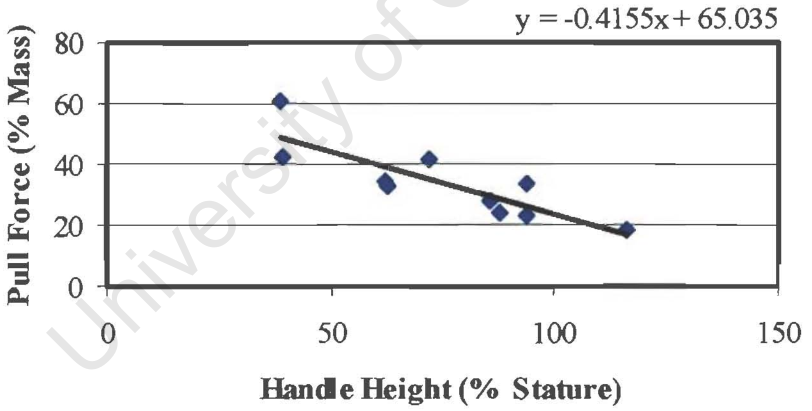


Figure 2.4: One-handed isometric pulling forces (% of body mass) versus handle height (% of stature) (Normalised data from Chaffin *et al.* 1983; Daams, 1993; MacKinnon, 1998).

Table 2.1: Comparison of isometric pull forces at different heights of origin between two similar studies.

Group	Handle Height (mm)	Kumar 1995a Force (N)	Kumar *et al.* 1995 Force (N)	% Difference
Females	1000	521	385	-26.1
Males	1000	763	537	-29.6
Females	1500	427	368	-13.8
Males	1500	744	469	-37.0

Few studies have examined the application of pull forces at extreme locations from the operator in the frontal plane. In most studies, while handle height is a manipulated variable, subjects are otherwise requested to adopt "comfortable" postures relative to the load handle in order to execute the pull exertions. In one-handed pulls, the origin of the pull will thus likely be in a parasagittal plane close to the mid-line of the body. In a two-handed pull, the origin of the pull is likely to be in the anatomical sagittal plane; if not, then slightly favouring a plane towards the dominant hand. MacKinnon (1998) examined single-handed maximum isometric pull force about various locations in the frontal plane. He found that the pull force was maximised at a location near elbow height (although absolute heights were employed in the experimental design) in a sagittal plane coincident with the shoulder joint for all three posture conditions. As the origin of the pull force increased in the vertical direction or away from the body in a horizontal direction, the pull forces became smaller. These findings were statistically significant.

A methodological variable which makes published literature difficult to compare is whether investigators choose to examine and report pulling activities at absolute cartesian locations or at locations relative to some anthropometric descriptor or landmark of the subject (e.g. stature, elbow height). Because the commonly accepted design practice is to provide adjustable workstations whenever practical, it seems advantageous for future research to derive pulling data and subsequent guidelines in terms related to subject morphology. Operator alignments could then be completed in a visual manner. In general, pull forces are maximised when handle origins are close to and directed towards the centre of mass of the subject. Future experiments should consider how moving the origin of pull away from optimal force-producing locations not only affects the magnitude of the pull exertions but how an operator might choose to perform the pull action while assuming awkward postures.

Load Resistance Characteristics

A typical question in pulling task research asks how task-related factors will influence the expression of strength. Much of the research to date has examined maximal isometric pull exertions. Grieve (1979a) conceded that static analysis has its limitations when assessing human-machine interactions. However, static analysis still has its benefits when attempting to simplify a complicated interface system. Furthermore, results from static analysis tend to be more simply communicated.

It would be a daunting task to summarise, in a tabular or graphical format, the findings of the research devoted to quantifying maximal isometric pull strengths. Differences in experimental protocols, subject selection and reporting strategies are the main contributors to these difficulties. It is unfortunate that, considering the volume of work in this area, a valid set of guidelines cannot be derived. These would certainly provide some basis to establish work practices for those activities including regular pulling exertions.

While isometric activations are not typical of those used *in situ*, methodologies that employ static models are superior in many aspects for testing the effects of independent variables. It is interesting that most experimental designs employing isometric activations have expressed little to no concern about standardising the distance the subject is away from the origin of pull (or the manner in which this is controlled is poorly reported in these methodologies), as the orientation of those segments containing agonist muscles will affect the inherent strength of the muscles at the time of activation (Hill, 1938). While this author knows of no literature which examines the effect of arm orientation (and hence muscle-tendon unit length) on isometric strength for upright pulling, Mital and Faard (1990) did report that pull strength, under isokinetic conditions, increased when the pull was initiated at longer arm reaches compared to pulls originating close to the body.

Research designs assessing maximal dynamic pulling forces have become more popular in the last several years. Understanding the relationship between velocity of pull and maximal pulling strength will have broad machine and workstation design implications. Garg *et al.* (1988) found that dynamic strengths were between 34 and 55% lower than comparable static strengths, yet the majority of the literature uses static models as the basis for task and workstation design. Not surprisingly, these authors found that peak pull velocity had a high negative association with dynamic strength.

Garg and Beller (1990) also reported decreases in maximal dynamic pulling strength with increases in pulling velocity. This finding was consistent over a range of relative handle heights. While high speed pulls resulted in a decrement in pull forces, subjects perceived the high speed pulls to be less strenuous and more comfortable. However, it is recommended that one-handed pulling tasks be performed at slow speeds to maximise strength capacities and to minimise the risk for overexertion injuries. Imrhan and Ramakrishnan (1992) also reported a decrease in pulling forces with increases in isokinetic speed. This relationship remained consistent throughout a protocol of various pull angles and postures.

Kumar (1995a) and Kumar *et al.* (1995) assessed the effects of isokinetic speed on pull force values. As in the previous section of this chapter, since the experimental protocols were virtually identical, the data can be easily compared. Table 2.2 reveals that for both males and females, the pull forces obtained under isokinetic conditions (speed of pull was 50 $cm.s^{-1}$ in both studies) were lower than those collected under isometric conditions. It is interesting to note that the decreases in the isokinetic pull forces with speed were not consistent between the two studies although the protocols were virtually identical. Differences in these values may be due to subject skill or motivation at the time of data collection. As discussed in an earlier section of this chapter, the authors do not comment on reasons for these differences.

Seated Pulling Postures

Workstations can be designed to allow operators to sit while executing pulling tasks, thereby allowing the operator to support various parts of the anatomy and to rest during periods of inactivity. Sitting will reduce the metabolic demands of an activity (Lehmann, 1966) which is certainly advantageous for an operator engaged in continuous, repetitive work.

Gaughran and Dempster (1956) were probably the first to examine the effects of operator posture on two-handed push and pull actions and their study represents one of the first ergonomic works employing classical mechanics analysis. These authors examined the force couples at all contact points between the operator and the workstation for various sitting postures in order to better understand how the operator created "leverage" while executing a pull force. As would probably have been predicted, the least pull force occurred when the feet were hanging and the trunk was orientated in a relatively upright posture. The maximum pull force increased as the head-arms-trunk segments moved away from the origin of pull because the turning moment increases proportionally to the length of the moment arm. The pull force was further increased when the subjects were allowed to brace their feet against part of the supporting seat. While these authors chose not to use a standing posture for comparative purposes, it does reflect the importance of the head-arms-trunk posture and operator strategy in executing pull exertions.

Table 2.2: Comparison of pull force decrements

	Sex	Height (mm)	Isometric (N)	Isokinetic (N)	Difference (%)
Kumar (1995)	Female	1000	521	363	- 30.3
	Female	1500	427	288	- 32.6
	Male	1000	763	553	- 27.2
	Male	1500	744	526	- 29.3
Kumar *et al.* (1995)	Female	1000	385	292	- 24.2
	Female	1500	368	253	- 31.3
	Male	1000	537	434	- 19.2
	Male	1500	469	390	- 16.8

Lara-Lopez *et al.* (1999) employed a static analysis approach to examine the forces applied to handgrips and pedals for a sample of 55 male industrial workers. The purpose of this research was to obtain information to assist in workstation design specifications. The methodology required the operators to make isometric, one-handed pulls while seated in a framed structure. Each subject repeated the pulls at five different elbow angles. The results can be explained by Hill's (1938) length-tension model for muscle, as the maximum static pull forces increased as the included angle at the elbow joint increased (range from 60 – 180 degrees). From this information, the authors extrapolated guidelines for the 5th to 95th percentiles of the population for this form of pull action.

Very little literature has compared the pull forces exerted during sitting with a comparable standing posture. MacKinnon (1998) found that maximum effort isometric pull forces about a variety of locations about the frontal plane were significantly reduced for a seated operator compared to a free-standing standing posture. Comparing the sitting condition to the free-standing condition, there was an average force decrease of 23%. In some circumstance there was up to 58% difference in the two postures. Whilst a sitting position will give the operator improved balance, these data indicate that it will be at the expense of force production.

Mital and Faard (1990) examined the effect of sitting and standing on the isokinetic pull strengths in the horizontal plane. They found that their subjects exerted on average 37% larger forces in a standing position compared to a sitting position. They concluded that this was due to the fact that a subject can better anchor the feet in a standing position and more effectively exploit the inertial properties of larger body segments, such as the HAT. Their claim that isokinetic strength capabilities are more highly correlated to dynamic task capabilities compared to isometric strength measures (although isometric strengths were not collected in this experiment) seems reasonable. However, it should be acknowledged that isokinetic muscle activations are not typical of *in situ* manual materials handling activities and future investigations should include isoinertial motions to better investigate this relationship.

MacKinnon and Stone (in press) compared the effects that standing and seated postures had on neuromuscular and cardiovascular responses during repetitive, submaximal isoinertial pulling tasks. They found that while a load of 15% body mass did not induce measurable neuromuscular fatigue upon these muscles over a 12 minute protocol of continuous pull exertions, the recruitment patterns of the monitored muscles were different between the standing and sitting postures. Analysis revealed that the activity levels were significantly increased for the deltoid and erector spinae (lumbar region) muscles in the standing condition compared to the sitting condition, while the opposite trend was observed for the latissimus dorsi. The recruitment levels of the trapezius remained consistent over both postures. These authors concluded that at similar workloads (*i.e.* about 15% of body mass), there may be benefits for a workstation that allows the operator to alternate between a seated and standing posture.

A sitting posture is considerably more stable than a standing posture for the operator. While the operator may also benefit from the metabolic savings provided by a seated posture, sitting may restrict the contributions of large body segments to the pull action. In an industrial setting that requires large pull force exertions, misapplying this sit-stand design principle can have a negative impact, most notably by reducing the force producing capabilities of the operator and placing large demands upon the more gracile upper body musculature. However, experimental comparisons between sitting and standing pull exertions, even at larger workloads, may be a desirable model to explore the coordination strategies adopted by operators.

Measurement of In Situ Pulling Forces

There is very little literature reporting measurements of upright, stationary pull exertion forces under actual industrial conditions. Van der Beek *et al.* (1999) suggest that it is very difficult to collect these data as a force measurement device is required between the hand(s) and the object being manipulated. In most circumstances, this instrumentation would interfere with the normal execution of the task. However, assessing the exposure-time histories *in situ* is an important future experimental endeavour if an understanding of how pull exertions impact upon operator injury is to be gained.

Van Wendel de Joode *et al.* (1997) measured the pull forces exerted by male ship maintenance workers using a instrumented strain gauge. For various maintenance activities requiring pull exertions, they reported forces ranging from 50 to 400N. While they noted that the majority of these observed efforts exceeded guidelines suggested by Mital *et al.* (1993), more importantly they observed that these efforts were performed under awkward postures and were sustained, in some cases, for extended periods of time.

Frings-Dresen *et al.* (2000) reported maximum pull exertion forces for a range of construction tasks, using an interfaced strain gauge to collect the measures. The reported range of peak pull forces was from 77.4 to 589.0 N. They also included the standard deviation values for these reported tasks. Calculated coefficients of variation range from 9 - 97%, indicating that there was considerable variability in these measures. This variability could be attributed to the lack of control of movement speeds (typical of data collected in the field), the instability of peak measures to represent time-histories, or perhaps the variability with which operators coordinate complex movements, such as pulling exertions.

The largest of the pull forces reported in both the van Wendel de Joode *et al.* (1997) and Frings-Dresen *et al.* (2000) seem to be within the range of maximum values reported under isometric and laboratory conditions (Chaffin *et al.* 1983; Daams, 1993; Kumar, 1995; Kumar et al., 1995; MacKinnon, 1998). It should be noted that in both of these studies details of posture and whether the pull exertions were created with one or two hands were not reported. These data appear to support the assumptions that continuous exposure to such pulling activities could lead to work-related injuries.

2.4 Kinetic Models to Assess Pulling Activities

Many manual materials handling activities can impose high compression and shear forces on the spine, particularly when a heavy load is handled or the moment arm of the load relative to the lower back is large. Consequently, lifting, lowering and carrying tasks have often been identified as high-risk activities for the development of low back pain. Because pulling activities often require forceful exertions, these actions are also expected to create high loads on the spine, as well as other aspects of the anatomy (Hoozemans *et al.*, 1998).

Gaughran and Dempster (1956) employed a static Newtonian model to examine balanced, two-handed push and pull activities. They illustrated how various sitting postures influenced the magnitude of the horizontal force exertions. Although static models are considered to provide limited kinetic information because the motion characteristics are not considered, this study did provide some insight into the inertial effects of the trunk segment on the magnitude of the outcome forces because of the systematic manipulation of the subject's posture within to the experimental design. This analysis also confirmed that there are two series of force couples in effect when a seated operator performs a push or pull action; one set related to gravitational forces and the other due to the horizontal forces.

Dempster (1958) continued this earlier work by extending the analysis to over 300 different pulling orientations, included standing, braced and sitting postures. While the purpose of the paper appears to have more to say about analytical technique rather than publication of empirical data (which would be difficult because only one subject was employed in the study), Dempster did make several important observations which still remain valid considerations for present day studies of pulling activities. Firstly, he questioned the common assumption that pull forces are simply a reflection of muscular strength. Rather, his mechanical analysis revealed that pull strength had much to do with the bracing technique employed by the operator, frictional factors of the workspace and segment inertial properties. Secondly, he reported that subtle changes in posture would affect the hand-foot force couple system, by influencing the direction and magnitude of the resultant vector. He indicated that in order to obtain maximal horizontal components of the net pull vector, a compromise between a large moment arm for the gravity couple and a smaller moment arm for the pull couple must exist. These findings indicate that certain "functional" postures are more likely to contribute to increased net pull force production by the operator. It should be acknowledged that even the simplest of mechanical evaluations could provide tremendous insight into issues of human performance.

Although these studies (Gaughran and Dempster, 1956; Dempster, 1958) proved to be invaluable contributions to the limited literature that existed at that time, dynamic models that reflect operator kinematics typical of pulling actions were required. The emergence of dynamic models was primarily due to improvements in data collection technology and the advent and availability of personal computers, which greatly enhanced the speed at which data could be collected, reduced, manipulated and analysed.

Lee *et al.* (1989) examined the dynamic pushing and pulling forces created when manipulating carts. They calculated the lower back stresses and the forces under foot using a biomechanical model developed by Lee (1982). Independent variables examined were height of the pull force exertion and movement speed. Although one of the first biomechanical models which allowed movement of the operator, it was applied on a cart-type pull and the results would not be representative of those of a fixed workstation. These authors determined that pulling resulted in higher low back loads than pushing. They also reported that as handle height increased from 660mm to 1520mm above the floor during pulling actions, the magnitude of the compressive forces acting on the lumbar spine also increased. These authors did make recommendations concerning optimal handle heights based on the information of this model, although these should be employed with caution, particularly in the design of a fixed workstation. Lee *et al.* (1989) suggested that perhaps lower handle heights should be used, thus decreasing the compressive forces exerted on the lower back. However, from a mechanical perspective, this would also decrease the normal force acting on the foot, thereby increasing the chances of the operator slipping while performing a pull. Thus, frictional properties between the foot and floor must be considered when making any recommendations or promoting safe practice guidelines. Results for the different walking speeds indicated that increased walking speed would increase the stresses acting on the lumbar spine. Although this result does seem intuitively obvious, it further highlights the fact that the inertial properties of both the operator and the load must be considered in any valid biomechanical analysis.

Andres and Chaffin (1991) later validated the model of Lee (1982) employing an inverse dynamics approach. Load cell and force platform data were synchronised with kinematic data in order to calculate the various kinetic parameters to be compared to model generated values. Although certain anthropometric and walking speed factors impacted on the residual differences between the measured and predicted force variables, these authors considered the biomechanical model of Lee (1982) to be reasonably successful in predicting lower spine forces.

Schibye *et al.* (1997) employed a 2-dimensional sagittal, static link segment model to examine the peak compressive and shear forces acting at the L4/L5 articulation of the lumbar spine while waste collectors pulled on two different carts (a 2-wheeled cart of mass 40kg and a 4-wheeled cart of mass 100kg). These values were compared to similarly derived kinetic data for lifting a load of refuse of mass of 25kg. The lift and carry versus cart techniques of waste removal were compared in order to assess the efficacy of an ergonomics intervention. The compression forces acting at L4/L5 were considerably smaller for both cart conditions than they were for the lifting technique. These authors reported no differences in the magnitude of shear forces between all three methods. However, the direction of the shear force changed from an anteriorly directed vector in the lifting technique to a posteriorly directed vector in the pulling techniques. The consequences of this change in vector direction were not discussed but surely would alter the potential mechanisms of low back pain or injury. Pulls on the cart handles were done with one hand and thus rotational moments at the L4/L5 would have existed, but were not calculated due to obvious model limitations. Thus, the reduction in the magnitude of compressive forces compared to the lifting technique may have been at the expense of increased torsional forces, which are also assumed to cause low back pain.

Kumar (1994) predicted back compressive forces during maximal two-handed isokinetic pushing and pulling activities, where the subjects' legs were securely braced in an extended position. Although the execution of the pull was pseudo-dynamic in nature, the compressive forces were only calculated at the point in time when the subject's horizontal pull force exertion was at a maximum. In actuality, the model values were derived from static assumptions (Cheng and Kumar, 1991). Kumar's (1994) results revealed that even though the push strengths were significantly lower than the pull strengths, the low back compressive forces were sometimes six times larger for push motions than pull motions. In light of these findings, he recommended that push activities in industry be reduced considerably. It is interesting to consider, however, that such a recommendation for task redesign may impose greater exposure to mechanisms that cause soft tissue injury during pulling.

Kumar's recommendations and findings are in direct disagreement with Lee *et al.* (1991) who found that pulling activities exposed the spine to larger stresses compared to pushing actions. So dramatic are these differences that Lee *et al.* (1991) calculated pull forces which would well exceed levels thought to damage the vertebral bodies (NIOSH, 1981). Kumar (1994) found considerably lower compressive forces, well within acceptable NIOSH (1981) values. There are three possible reasons that explain, in part, the different findings of Lee *et al.* (1991) and Kumar (1994) other than the fact that two different kinetic models were employed. Firstly, the subjects' upper bodies in Lee *et al.*'s experiment were almost static, while the lower bodies of Kumar's subjects were physically braced to eliminate all motion. The second explanation is that the orientations of the upper body were dramatically different. In the case of Lee *et al.* the forward leaning torso posture used in the experiment dramatically increases the loads on the lower back just to maintain stability, irrespective of the model used to predict these forces. Finally, the backwards lean of an operator in pulling a cart device might be restricted due to limited space under the cart (van der Beek *et al.*, 2000). Limiting foot positioning in this respect has been shown to influence the exertion of pull forces (Ayoub and McDaniel, 1974). Further research is still needed to compare the capabilities of a back-arm aggregate rather than the influence of lower limb involvement in pulling actions.

Considering that in both studies the subjects were requested to exert maximal efforts (although at different speeds and types of muscle activations), this comparison provides a fine example of how experimental design and model assumptions will impact on the predictive validity of experimental data. The somewhat contradictory findings between these two studies reaffirm that cart-like and fixed workstation pulling are really dissimilar manual materials handling activities. Furthermore, one must consider that the pathomechanisms responsible for operator injury are different between these two types of pulling activities.

While there is still much research needed to better understand the kinematics of upright pulling, eventually biomechanical models will have to be employed to gain insight into the kinetics of the operator - workstation system. In this respect, several recommendations are made by the author regarding the experimental design of future studies examining pulling motions:

(1) In order to reduce the complexity of the biomechanical model, both Lee *et al.* (1991) and Kumar (1994) requested the subjects to exert two-handed maximal exertions. This experimental control, however, restricts the manner in which the trunk can move in three-dimensional space by limiting the rotational component of the spine. Trunk rotation is not only typical of many manual materials handling activities, it has also been identified as a potential mechanism causing low back pain. Therefore, development of future biomechanical models should incorporate axial moments, making them more applicable for assessment of one-handed exertions.

(2) Both of the aforementioned studies required the subjects to exert a force in an isokinetic manner. Although it is important to control as many influencing factors as possible, in reality the operator will have to interact with loads under the influence of many forces (i.e. gravity

and friction). The operator must overcome the initial resistance of the load to motion and then move the load in a controlled fashion. While all ergonomists strive to measure operator function during actual industrial activities, isoinertial weight-training machines, for example, would be better systems to provide a resistance more like those found in industrial settings.

2.5 Electromyographical Analyses of Pulling Activities

While the Italian Francesco Redi has been credited with being the first to document muscle-generated electrical activity in 1666, it was Luiggi Galvani who in 1791 first described the relationship between electricity and muscle contraction (Basmajian and De Luca, 1985). Since then, recordings of electromyographic activity from muscles have been used to better understand muscle function and coordination strategies.

The basic principles of neurophysiology will not be reviewed in this work, and the reader is referred to an in-depth textbook on the physiology of muscle contraction (Basmajian and De Luca, 1985). For the purposes of this review, it will be assumed that a neurally active muscle will emit an electrical potential, which will cause a depolarizing wavefront across the surface of a superficial muscle. It is the electrical wavefront from a particular site on a muscle that can be measured.

Electromyographical signals are analysed to assess the activation state of a specific muscle. This information may be used to evaluate the temporal sequencing of a muscle within the context of coordinated movement strategies, the relative magnitude of activation and thus a muscle's potential for contribution to the net resultant joint moment or the analysis might examine the change in fatigue state over an extended period of activity. Thus, signal assessment may be done in either the temporal or frequency domain. EMG analysis can provide answers to many kinesiological or ergonomic questions, as long as the investigator employs the correct analytical techniques and is well aware that the EMG signal is very sensitive to errors from a variety of sources (Kumar, 1996). EMG analysis has been adopted as an invaluable tool in the verification of the complex interaction of muscle functions in complex activities (Andersson *et al.*, 1996) and can provide insight into the manner in which task variants may be executed (Ladin *et al.*, 1989).

Relatively little ergonomic research assessing pulling activities have utilised EMG technology to better understand commonly employed movement coordination strategies. The primary use of the technology has been either to examine muscle recruitment patterns or to validate kinetic models used to assess forces acting on the operator.

The electromyographical activity of the erector spinae and the rectus abdominus have been used as input parameters in two dimensional sagittal plane biomechanical models in order to verify the predicted forces of these muscles. The forces of the erector spinae and the rectus abdominus are necessary in a systematic prediction of the compressive and shear forces of the lower spine during various manual materials handling activities (Lee *et al.*, 1989). Such a validation approach has achieved moderate success when used for static postures and activities, although the validity of using EMG records to predict individual muscle forces or spinal load decreases during dynamic activities due to many factors (Granata and Marras, 1995).

Lee *et al.* (1989) applied a biomechanical model to examine isometric pushing and pulling activities for a variety of postures. They found low correlations between the EMG activity and the predicted muscle forces, particularly when the torso flexion angle was increased. Like other researchers (Leskinen *et al.*, 1992), Lee *et al.* suggested that passive muscle forces and ligamentous structures, which emit no EMG signal, counteract the increasing forward bending moment due to gravity. In addition, simplified models that are limited in the number of sampled muscles will provide limited information regarding the load sharing strategies likely to occur during complex movements (Ladin *et al.*, 1989).

Lavender *et al.* (1998) assessed the impact of lifting belts on the magnitude of maximum isometric pulling forces, the magnitude of the EMG signal of agonist and antagonist muscle groups and the bending moments created during a variety of pulling conditions. Their results revealed that there were significant differences in the recruitment magnitudes and patterns of the tested muscles, indicating that the strategy adopted to generate a pull force must be posture dependent. Much to their surprise, they found that the lifting belt, a common ergogenic aid utilised in industry, had no significant effect on the EMG profiles between similar postures. This observation was also supported by the fact that regardless of the posture tested, the peak pull forces were not affected by the use of a safety belt. This suggests that neither mechanical nor metabolic savings may be realised when using lifting belts in pulling activities.

Kumar (1995b) used EMG to compare the function of the bilateral erector spinae, external oblique and rectus abdominus muscles during raking activities employing a normal and modified garden rake. Raking requires the operator to perform alternating pushing and pulling activities to level ploughed soil. The results from his study suggested that rakes which were commercially promoted as being "ergonomically correct" in fact increased the neural activity of the examined muscles, suggesting an increased muscle force and perhaps an increased load on the lumbar spine region. This data supported previous research, which indicated that predicted forces acting on the spine were increased with the use of rakes with modified handles (Kumar and Cheng, 1990).

It is recognized that there is a lack of EMG data on muscles controlling the shoulder complex during pulling exertions, particularly for upright pulling motions. This is surprising considering that Hoozemans *et al.* (1998, 2002) have suggested that this manual materials handling activity places an operator at risk for shoulder and neck injuries. While benchmark EMG data describing muscle function under varying conditions of pulling will provide insight into the aetiological factors relating pull exertions to injury, these data can also be synchronized with kinesiological information collected simultaneously from the trunk complex (and other aspects of the anatomy), to provide a better understanding of global coordination strategies adopted by an operator under varying conditions requiring pull exertions.

2.6 Operator Injury and Pulling Activities

The epidemiological data in ergonomic research is very important to the discipline, not only to identify a task or an occupation thought to cause operator injury (Forde *et al.*, 2002), but also to determine the efficacy of an ergonomics intervention programme. While the focus of this research project is not to investigate the incidence or prevalence of worker injury, an understanding of this literature is imperative for the design of studies attempting to associate injury mechanisms to pulling tasks.

Many authors have suggested that pulling activities are risk factors for low back pain (Snook *et al.*, 1978; NIOSH, 1981; Garg and Moore, 1992, Hoozemans *et al.*, 2002). While pulling tasks may be performed less frequently than lifting tasks (Lavender *et al.*, 1998), these actions still expose the low back anatomy to large compressive and shear forces and high bending moments (Chaffin *et al.*, 1983; Chaffin and Andersson, 1991). NIOSH (1981) suggested that 20% of the claims for low back pain could be attributed to pushing and pulling activities, while other studies have reported lower attributable rates of 9 to 18% (Snook *et al.*, 1978; Lee *et al.*, 1991; Garg and Moore, 1992). Several explanations may be offered as to why these rates vary from study to study: characteristics of the working situation (van der Beek *et al.*, 1999), healthy worker effect (Kuiper *et al.*, 1999), or perhaps the reluctance in some industries or settings for workers to admit to incapacity due to pain or fear of being denied further employment or advancement.

Whilst there is a reasonable body of epidemiological research into the general area of manual materials handling, there has been limited documentation focused specifically on pulling activities and generally these findings have been found to be inconsistent from study to study (Kuiper *et al.*, 1999). Frymoyer *et al.* (1980) and Damkot *et al.* (1984) employed a retrospective design using questionnaires and suggested that occupational tasks requiring pulling actions (among others) were significantly related to patients reporting incidences of low back pain. Van der Beek *et al.* (1993) reported a significant odds ratio (1.7) for habitual lumbar region discomfort for lorry drivers who performed regular wheeled-caged pushes and pulls, in comparison to drivers who were not required to perform pushing and pulling activities. Fuortes *et al.* (1994) reported a calculated odds ratio risk (1.08) in a nursing population for developing low back pain due to pulling activities. In a more recent study, Hoozemans *et al.* (2002) reported a significant prevalence rate ratio (2.15) for pulling exertions and low back pain, compared to a reference group. This study also examined the dose-response relationship between pulling activities and reported shoulder pain complaints. A prevalence rate ratio of 2.0 was reported, a similar finding as Van der Beek (1993), suggesting that pulling (and pushing) actions are likely a specific risk factor for shoulder pain complaints.

It remains difficult to measure dose-response gradients or causative mechanisms when attempting to associate occupationally-related pulling activities and incidence of low back and shoulder pain. In epidemiological studies, many confounding factors exist and are often difficult to control from a statistical/analytical perspective. The presence of various psychosocial factors, for example, often leads to an underestimation of the importance of mechanical loading factors in logistical regression models. Furthermore, low back and shoulder pain does not always present as a precise structural or soft tissue abnormality (Damkot *et al.*, 1984) and in themselves are not great outcome measures. In future epidemiological studies, prospective designs, under well-controlled conditions, are required to confidently identify the relationships between occupational demands, operator capacity and injury manifestation.

While pushing and pulling movements are very distinct from each other, these are rarely considered independently of each other in the epidemiological literature. From a biomechanical perspective, mechanisms of injury will likely be different as a result of pushing and pulling activities, given the known differences in calculated forces and moments acting at various locations of the body (*e.g.* Schibye *et al.*, 1997). While push-pull activities are common aspects of a repetitive movement cycle typical of many industrial activities, future research should attempt to consider these manual materials handling activities as distinctly separate movements.

Hoozemans *et al.* (1998) published a review of those pushing and pulling task-related risk factors that have been associated with musculoskeletal disorders. They employed a conceptual model published by Westgaard and Winkel (1996) to establish a basis for identifying the incidence of external exposures to the worker, such as work method, posture and movement strategies, and outcome internal exposures, such as compressive forces acting on the spine of the lower back.

The basis of the Westgaard and Winkel model is to relate the external exposure acting on the operator to the internal exposures which modify the acute responses such as physiological fatigue or mechanical stresses acting at pertinent body segment articulations. While this model might be successfully applied to lifting activities, it is more difficult to apply in a situation where pulling exertions are created. It is often difficult to measure the magnitude and direction of the pull exertions without some measurement device interfaced between the operator and the object upon which the force is being applied (van der Beek *et al.*, 1999) and self-report of pull loads have been found to be unreliable (Wiktorin *et al.*, 1996). These data must be carefully quantified, for example, if an inverse dynamics approach is to be employed to predict resultant joint forces and moments acting at various articulations of the operator. Until a relevant metric can be established to assess operator exposure to the demands of pulling exertions, it will remain difficult to assess the impact of this manual materials handling activity on musculoskeletal disorders, especially if pulling is only one component in a multiple-task job (Dempsey, 1999).

Hoozemans *et al.* (1998) identified possible mechanisms related to injury as being possibly psychophysical, biomechanical or physiological in nature. These authors reviewed past studies which used these methodological approaches to establish guidelines for pulling limits and subsequently, whether adherence to these limits had the potential to reduce operator risk. These authors identified two main areas of the operator's body that are susceptible to pain and injury as a result of pulling tasks: the lower back and the shoulder region.

The majority of the epidemiological research regarding the deleterious effects that manual materials handling activities have on the operator has focused on the low back and generally the manual materials handling activity considered is lifting. It is generally agreed that the mechanical loading of the lumbar spine is a significant risk factor for the development of low back pain (Kumar, 1999; Marras, 2000). However, it is also recognised that it is not simply the magnitude of these loads, but the kinematic patterns, as well as operator profiles and environmental conditions (Marras *et al.*, 1995), which have to be better understood in order to establish effective injury prevention strategies, regardless of the manual materials handling activity being investigated. Low back pain in all likelihood has a multi-factor aetiology, which makes the interpretation and application of epidemiological models even more difficult (Dempsey, 1998).

Other aspects of the anatomy should also be at risk for musculoskeletal injuries given the large forces exerted by the hands. These include upper extremity injuries, specifically the shoulder and elbow, although there have been a minimal number of studies in this respect. Van der Beek *et al.* (1993) found significant increases in complaints of pain of a musculoskeletal nature in areas other than the lower back, including the neck, shoulder and lower extremities, in lorry drivers who regularly pushed or pulled trolleys. Others have found that upper extremity and neck complaints have been associated with working posture and height of force application (Bjelle *et al.*, 1981; Anderson, 1984).

Injury statistics for occupational accidents have been typically divided into two broad categories: chronic and acute. While musculoskeletal injury due to repetitive motions and/or exposure to detrimentally high loads are considered chronic injuries, and are typical of those described earlier in this section, the mechanisms by which acute injuries occur from slips and falls also demand attention by ergonomists. Operator posture imposed by poor workstation design and more specifically the direction of the pull force vector relative to the operator can affect the kinetics of the foot and floor contact (Grieve, 1983: Lee *et al.*, 1992). Acute injuries from slips and falls, like those chronic injuries previously addressed, add to the total economic and personal costs of injury and accidents and may be reduced, if not eliminated, by proper workstation design and a better understanding of the movement strategies associated with pulling activities.

The task of better identifying mechanisms of injury during pulling activities has become much more complicated in recent history. The conflicting findings in the literature may be attributed to several factors: varying or inconsistent job descriptions, inadequate identification of contributing workstations features, a move towards mechanisation, job rotation and multitasking, to name but a few. Intervention strategies have typically focused on reducing the extreme loads the operator has to manipulate or redesigning workstations to accommodate operator morphology. Perhaps a better understanding of the inherent manner in which human operators create these pulling forces will positively influence experimental hypotheses and workstation design in the future.

Chapter 3

Isometric Pull Forces in the Sagittal Plane

This paper investigates the differences in maximal isometric horizontal pull forces in the sagittal plane about a frontal plane work envelope. Eight subjects produced maximal isometric horizontal pulls about 32 positions in the frontal plane for each of three different postural conditions: free standing, fixed standing and seated. Four horizontal positions (0, 200, 400, 600 mm relative to the mid-line of the body) in the sagittal plane at four vertical heights in two standing postures (1070, 1470, 1610, 2000 mm from the floor) and one sitting posture (220, 620, 760, 1150 mm from a seated reference position) were tested for both the left and right hand under all three postural conditions. Experimental findings reveal that the largest horizontal forces were produced at a height of 1070 mm in the standing postures and 220 mm in the sitting posture and were within 200 mm to the left and right of the mid-line of the body. These findings confirm that workstation designs should position heavy materials near the mid-line of the body, at or about elbow height to take advantage of operator's force-producing capabilities in the sagittal plane.

3.1 Introduction

There is clearly a need in third world countries, particularly those in Africa, South America and Asia, to reduce the high incidence of occupational accidents and work-related musculo-skeletal problems within manual material handling occupations. Although there is a growing awareness of the need for qualified ergonomists in industrial developing countries, the realities are that most companies rely on factory managers and, at best, safety officers, to recognise work hazards and to implement ergonomic intervention programmes at the worksite. Furthermore, those persons directly involved in work productivity and safety do not have an extensive educational background in kinesiological and ergonomic theory, nor do they have access to sophisticated assessment equipment. In this context, evidence of worksite hazards that can be identified at minimal cost, without esoteric instrumentation, will provide direction towards practical, if not definitive, strategies for the reduction of both acute and chronic work-related injuries.

Considerable research has been devoted to the application of reach envelopes in workstation design (Clark and Corlett, 1984). Although a variety of industrial tasks require forces to be exerted about a specific reach envelope, little information exists regarding an operator's force capacity within movement planes.

In some tasks it is necessary to produce a maximal force within a reach envelope. However, in most task designs, operators have to exert repeated submaximal exertions, often in awkward postures. In such situations, even small forces, relative to a maximum isometric activation, can cause occlusion to blood flow (Barnes, 1980), which in turn decreases the time to onset of muscular fatigue and increases the potential for chronic injury (Rodgers, 1987). Thus, it is necessary to understand the relationship of maximal force production within a movement plane to determine the acceptable levels of submaximal forces that can be exerted within the reach envelope or workspace.

Horizontal force production in the sagittal plane is dependent on operator position, kinanthropometry and biomechanical factors (Chaffin *et al.*, 1983; Snook and Ciriello, 1991). These factors, in relationship to the workspace design, will dictate the magnitude of the load force that can be applied to a handle or object that acts in a horizontal direction, that is, a push or pull.

Many studies that have examine push-pull capabilities have employed methodologies that have included bracing of the feet or other body parts (Kroemer, 1974), exploiting the inertial properties of large body segments (Daams, 1993; Grieve, 1979a; Lee *et al.*, 1991; Lee, 1995), or applying the horizontal forces with body parts other than the hands (Webb and Associates, 1978). These strategies might maximise the magnitude of the push or pull forces but do not necessarily reflect typical strategies common to work stations where muscular control is needed to control discrete movements or prevent accidents due to slips and falls.

Maintaining a predominant posture for extended periods of time can lead to muscular fatigue. Therefore, a desirable design strategy is to allow the operator a choice of working positions or postures within a workspace. Typically, an operator may sit or stand, and a freely chosen posture can be adopted which adequately accommodates the task demands and the constraints of the workspace (Fothergill *et al.*, 1991). However, changing positions in a specific workstation will not only alter the reach envelope, it could change the functional muscular synergies that produce the horizontal forces. While standing, large muscle groups, foot-floor friction or inertial factors can be used to create a horizontal force. Smaller muscle groups may have to be recruited to effect the same horizontal force when the operator assumes a seated position or when movement within the workspace is restricted. This observation is particularly true when the standing and relative seated heights are not the same within a workstation.

The stability of the operator within the workstation will impact on the magnitude of horizontal forces produced. In circumstances requiring large horizontal force exertions, a standing operator will choose a large base of support, straddle the legs and center the body relative to the direction of the applied force (Chaffin *et al.,* 1983). This strategy should limit the possibility of slips and avoid movement of the centre of mass outside the base of support. In a seated position the operator is limited as to how stability can be achieved. The feet will not be as effective in creating frictional forces that can contribute to the resultant horizontal pull. The size of the base of support will be dictated by the physical characteristics of the seat. Also, extended reaches from a seated position may be necessary in order to actuate forces in a sagittal plane, which moves the centre of mass nearer the edge of the base of support, thus creating a less stable system.

Whether in a standing or seated position, the location of controls, levers or heavy materials may be such that desirable working postures are unobtainable or impractical. In workstations where horizontal forces have to be regularly applied at the boundaries of the frontal plane, those operators who have longer arm segments can more easily access extreme positions. As the size of the operator decreases, the ability to reach extreme positions and apply horizontal forces may also decrease, while the level of instability and the propensity for injury to the lower back will increase.

The purpose of this study was to examine the effects of pulling posture on the forces created at diverse positions within a frontal plane. Force profiles within a reach envelope will provide needed information to further improve workspace design and provide insight into musculo-skeletal injury aetiology. It is hypothesised that as the origin of pull moves superiorly and laterally from the subject's relative centre of mass location the pull forces will decrease, regardless of the posture assumed.

3.2 Methods

Eight subjects (5 male and 3 female) ranging in age from 20 to 43 years (mean 28.5 ± 8.2 years) participated in this study. Subject characteristics can be found in Tables 3.1 and 3.2. An attempt was made to select subjects who possess similar morphological features, specifically in the linear anthropometric measures. However, the variability in subject mass, and presumably strength, was higher than that of stature. This subject selection approach was considered adequate to assess the effects of mass-related strength and to limit the potential effects of mechanical advantage often associated with subjects who have longer limb lengths. No subject reported previous or current history of back, neck, shoulder or elbow trauma. All subjects reported a right-hand dominance. The subjects were requested to bring ankle-supported shoes with a slip-resistant sole to the data collection session. Prior to data collection, subjects were given verbal instruction of the experimental protocol and informed consent was obtained.

Table 3.1: Subject anthropometry.

	mean	**SD**	**CV**
Age (Years):	28.5	8.2	28.8
Mass (kg):	71.3	9.5	13.3
Standing Stature (mm):	1720	51	3
Sitting Stature (mm):	905	33	4

Equipment

An aluminium handle (grip diameter of 15 mm) was mounted on a uni-directional load cell (Load Cell Service, Pretoria, South Africa). The length of the handle and load cell assembly was 380 mm. The load cell has a maximum peak capacity of 2000 N and a sensitivity of 0.5 N. Maximum pull load was stored on a digital peak hold unit. The load cell was mounted to a series of parallel bars, positioned perpendicularly to the floor. This assembly allowed the load cell to be positioned at any desired vertical height or horizontal distance relative to the floor or seated reference point. Figures 3.1 and 3.2 depict the experimental set-up.

Table 3.2: Functional anthropometric measures.

	Standing			**Sitting**		
Measure	**mean**	**SD**	**CV**	**mean**	**SD**	**CV**
Vertical Grip Reach (mm):	2048	52	3	1248	36	3
Eye Height (mm):	1607	58	4	785	43	5
Shoulder Joint Height (mm):	1388	50	4	580	41	7
Elbow Height (mm):	1092	26	2	286	32	11
Lateral Span* (mm):	1493	49	3			
Forward Reach* (mm):	603	30	5			

* - measured with closed fist

Experimental Design

Each subject went through a total of 96 single-handed maximal isometric pulls. Three postural conditions were considered: feet free to assume any stance; feet fixed in a parallel position with a distance of 75 mm between the medial borders; or seated position with the feet held off the support surface. In the free standing postures, the most anterior aspect of the forward foot had to be 380 mm from the anchor point of the load cell, while the other foot was free to assume any orientation. In the fixed standing position, the anterior aspects of both feet were positioned 380 mm from the anchor point of the load cell. In the seated position, the patellae were positioned 380 mm from the anchor point of the load cell. The elbow and shoulder angles were not controlled. Four absolute pull heights were used. In the free and fixed standing conditions, the pull heights were 1070, 1470, 1610, and 2000 mm, all measured from the floor. In the seated condition, the pull heights were 220, 620, 760, and 1150 mm, all measured from a seated reference point which was defined as the height of the seat pan. The height of the seat pan was 870 mm from the floor. Thus in all three conditions, the absolute heights of the pull were approximately the same, the seated posture allowing for compression of the chair seat and soft tissue of the buttocks and thighs. Given the small variation in the anthropometric measures of the subjects employed in this study, these absolute vertical heights can be considered to approximate their elbow, shoulder, eye and vertical reach heights respectively. At each height, a maximal pull at 0, 200, 400 and 600 mm from the mid-line of the body was attempted. These positions (four vertical heights by four lateral deviations) were attempted by both the right and left hand. These series of 32 frontal plane positions were repeated for each of the three conditions. The postural conditions were presented to each subject in random order. In all conditions, the foot-floor or subject-chair interfaces were considered to be optimal and not a limiting factor in the production of horizontally directed pull forces.

Procedure

The subjects were instructed to produce maximal forces in a horizontal direction, away from where the load cell was anchored. The subjects were asked to pull the handle of the load cell in a slow, progressively increasing fashion and hold the maximal exertion for a period of three seconds. This procedure avoided sudden accelerations on the load cell handle that would have resulted in a force overshoot. If a "jerking" movement occurred, the trial was rejected and then repeated. In both the standing and seated postures, subjects were instructed to maintain an erect trunk posture. Subjects were instructed to use the arm musculature as the primary means of force production and not to lean backwards to assist in the pull. Subjects were continually reminded to adhere to these criteria.

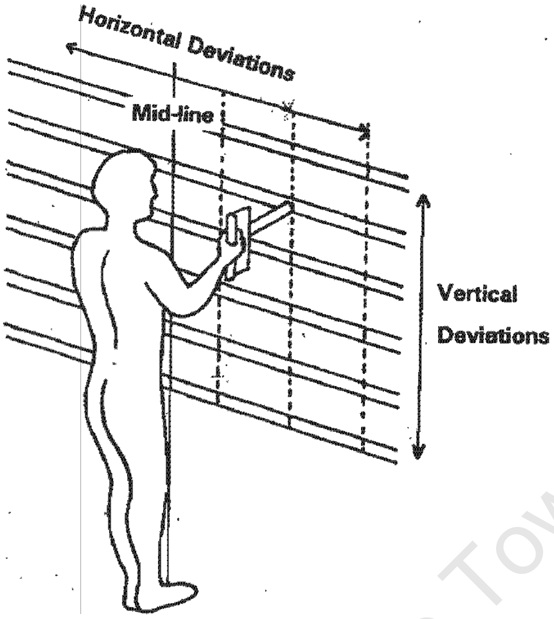


Figure 3.1: Illustration of location of horizontal pulls in a standing posture.

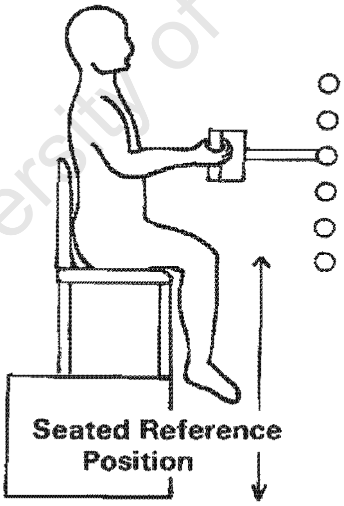


Figure 3.2: Illustration of sitting posture.

The subject was instructed to grasp the vertically-orientated load cell handle in the most comfortable manner and to keep this hand position constant throughout the data collection session. The investigator ensured that the sternum was positioned in the same plane as the 0 mm lateral deviation position before each pull was attempted. If this position changed during the collection of data, the trial was rejected and subsequently repeated.

Peak horizontal load force was recorded for each trial. Adequate rest was given between attempts while the investigator changed the position of the load cell handle for the next trial (approximately 60 seconds) and the subject was encouraged to rest if experiencing any manner of fatigue. The order of the efforts for each pull location was randomly assigned. Halfway through the data collection, a break was taken in order to gather the anthropometric measures reported in Table 3.2. Definitions of these measures can be found in Pheasant (1988). At the end of the total 96 attempts, a minimum 16 random pulls were attempted. These values were compared to the initial attempts to assess repeatability and possible effects of fatigue. These data for each subject were compared using a paired t-test. The average mean difference for all the subjects was found to be 0.286 N and the average p-value to be 0.5406. Based on these statistics, the measurements were deemed to be repeatable and not significantly influenced by fatigue.

3.3 Results

The data were analysed to assess the effect of posture and point of application within the frontal plane on the magnitude and variability of the horizontal pull forces produced in a sagittal plane. The statistical analysis was designed to assess if there were directional trends in the horizontal pull forces due to the independent variables.

Group mean, standard deviation and coefficient of variation values for anthropometric measures can be found in Tables 3.1 and 3.2. The mean, standard deviation and coefficient of variation data for the horizontal pull forces in the free standing, fixed standing and seated positions can be found in Table 3.3, respectively. A one-way analysis of variance (ANOVA) was used to test the differences between the left and right hand. No statistically significant differences were found (p=0.8850) between the left- and right-hand horizontal pull force data, thus these data were combined for the rest of the statistical analyses.

A multi-factorial analysis of variance (MANOVA) was used to assess the effects of vertical pull height, horizontal deviations in the sagittal plane from the mid-line of the body and posture on the magnitude of the horizontal pull force (Table 3.4). There was a significant difference in the horizontal pull forces across all vertical heights (p=<0.0001). In general, as the vertical height decreased, the horizontal pull forces increased. The MANOVA revealed that a significant difference existed between the pull forces produced along a horizontal axis (p=<0.0001), except for

Table 3.3: Horizontal pull forces (N) in the three experimental positions.

Vertical Height (mm)	Horizontal Position (mm)	Free Standing mean	SD	CV	Fixed Standing mean	SD	CV	Seated mean	SD	CV
2000	0	127	43	33	90	24	26	95	36	37
	200	120	42	35	91	23	25	98	32	32
	400	109	30	27	85	22	25	88	28	32
	600	99	26	26	77	20	26	75	26	34
1610	0	162	48	29	114	25	22	142	37	26
	200	151	42	27	114	27	24	134	37	27
	400	132	40	30	99	27	27	111	38	34
	600	111	33	29	81	24	29	93	37	39
1470	0	196	63	32	134	34	25	164	50	31
	200	163	47	28	131	31	23	148	40	27
	400	141	40	28	105	24	22	115	30	26
	600	122	36	29	92	32	34	91	30	32
1070	0	241	88	36	164	40	24	204	57	28
	200	208	63	30	154	40	26	194	58	30
	400	172	50	28	125	32	26	138	51	37
	600	142	46	32	96	32	33	90	31	34

Table 3.4: Multi-factor analysis of variance of the effect posture, vertical and horizontal position on pull force magnitude.

Source	df	SS	MS	F-Value	P-Value
Posture	2	2200.9	1100.4	68.1	<0.0001
Vert.	3	4325.0	1441.7	89.2	<0.0001
Posture*Vert.	6	158.2	26.4	1.6	0.1358
Hor.	3	3620.7	1206.9	74.6	<0.0001
Posture*Hor.	6	194.0	32.3	2.0	0.0635
Vert*Hor.	9	860.6	95.6	5.9	<0.0001
Posture*Vert.*Hor.	18	75.7	4.2	0.3	0.9992
Residual	720	11640.7	16.2		

the 0 and 200 mm conditions (p=0.0827). Mean data reveals that as the distance away from the mid-line of the body increases, the horizontal pull forces decrease. There was a statistically significant difference between all three postures (p=<0.0001), with the free standing posture producing the largest and the fixed standing posture exhibiting the smallest horizontal pull forces.

3.4 Discussion

When producing a pull from diverse points in the frontal plane, it is desirable to apply the force from a position in which the operator can assume a comfortable posture, minimising over-extended reaches or twisting of the trunk. However, the design of the workspace, the anthropometric characteristics of the operator and the direction and point of application of the force will all affect the magnitude of the horizontal pull forces that the operator can exert (Chaffin and Andersson, 1991).

A large number of anthropometric and biomechanical factors can influence the exertion of a pull force, therefore the conditions of the experimental set-up are of primary importance. Controversy exists in the literature as to how postural constraints affect force application, as well as whether posture should be standardised (Warwick *et al.*, 1980) or free (Daams, 1993; Fothergill *et al.*, 1992) during the collection of empirical data. If the objective of the research is to develop normative data then stringent postures during data collection must be controlled. Systematically defined hand, foot and segment orientations may well be considered as criteria for methodological reproduction or comparison between studies and can be more easily used in predictive models. One has to be careful not to make the data collection so artificial that it does not reflect the realities of the workstation and the characteristics of the operator. Standardisation should affect those body parts which are exposed to external reaction forces, such as the hands and feet, allowing the rest of the body to freely adapt to the constraints of the workspace.

In regard to the current research, the aims were to assess the changes in the pull force profiles due to posture and the location of the pull force. Tables 3.1 and 3.2 reflect the small magnitude of variability amongst the subjects in all the linear anthropometric scores, as the coefficient of variation scores ranged from 2 to 11%. As a post-hoc analysis, the vertical grip length and the lateral span length for each subject were assessed as a percentage of stature. These data also proved to have a small amount of variability (1% for vertical grip relative to stature and 2% for lateral span relative to stature). So it may be correct to assume that the subject anthropometry did not exert significant effects on the magnitude of the horizontal pull force. Therefore the discussion can focus on the effect of posture and those biomechanical factors associated with each posture condition upon the magnitudes of the pull forces at each experimental location.

Sagittal plane horizontal pull forces within the frontal plane

The load cell employed in this research limited measurement to one direction. Although the subject was instructed to exert a force in a horizontal direction, perpendicular to the anchor point of the load cell, it is possible that an out-of-plane resultant force was actually created. This might partially account for the differences in the magnitudes of the forces at each location. It is recognised that these out of plane forces may have been necessary for body stabilisation and could be an integral part of operator stability within a workstation (Pheasant and Grieve, 1981; Pheasant *et al.*, 1982) and furthermore, may account for the mechanism of soft tissue injury under these pull exertion conditions. As such, future methodologies should attempt to measure the pull forces in all three dimensions. However, for the purpose of this discussion, it will be assumed that the measured forces reasonably represent a significant proportion of the resultant force vector.

Statistical analysis revealed that the ability to apply a maximal force in the sagittal plane is dependent on the vertical and horizontal point of application of the pull (see Table 3.4). Chaffin *et al.* (1983) found that pulling forces were reduced in "high" pull situations. In their study, the high pull was effected at levels above 1520 mm from the floor. In vertical reach postures, the action is limited to an elbow flexion moment. Results from this study support past findings (Chaffin *et al.*, 1983; Fothergill *et al.*, 1992), that horizontal pull force decreased as the vertical displacement from the floor increased (see Table 3.3). Elevation of the arm can increase levels of co-contraction, which

Variability of force magnitudes

Previously discussed was the fact that the subjects exhibited little variability in the anthropometric measures, yet there was large variability in the magnitudes of the pull forces across the different postures (refer to CV scores in Table 3.3). As a *post hoc* analysis, the maximum pull force for each subject was related to body mass. The maximum pull force for all subjects was located in the mid-line position at the lowest experimental height either at the 0 or 200 mm lateral displacement. As with most studies that examine maximal force production, the variability associated with this ratio was large (CV=31%). This suggests that although the morphologies of the subjects were similar, their muscular capacities were not. These results reflect the inherent difficulty of developing absolute strength norms. Future research should perhaps be focused on factors such as posture and the location of the application of the force as a basis for predicting allowable or maximal permissible loads, as well as injury potential.

The extent to which a posture is fixed, whether this is due to an experimental methodology or a restricted workstation, will influence the degrees of freedom available to a person to create a pull force at a prescribed location. As the freedom to adopt a posture increases, the ability to take advantage of strength capacity should also increase. Daams (1993) suggested that when measuring whole-body movements, freely chosen postures tend to be more reproducible for an individual. Therefore one should expect an increase in the variability between subjects of diverse muscular strength. The CV scores in Table 3.3 support this statement. The variability among the subjects to produce a horizontal pull force is largest in the free standing position, particularly at locations near the mid-line of the body. Perhaps the magnitude of the variability of horizontal pull force production over diverse locations about the frontal plane warrants further investigation with a larger sample of subjects, who possess more diverse morphologies than those subjects used in this study.

Representation of data in relative magnitudes

While the original data were collected in absolute measures, as part of a *post hoc* analysis, a multiple factor regression was used to assess the relationships between normalised measures for the free standing and sitting trials. It was decided not to perform the same analysis upon the fixed standing data given the restricted ability of the subject to produce a maximal effort under this condition, in comparison to the free standing and seated conditions. The absolute measures were normalised in the following manner. The vertical displacements were expressed as a percentage of stature for the free standing trials or of sitting height in the case of the sitting trials. The lateral displacements were expressed as a percentage of one half of the lateral span, which were measured with the fists closed. The horizontal pull force data were expressed as either a percentage of the pull force measured at the 1070mm height in the standing trials or the 220mm height in the sitting trials. These were the locations where, on average, the largest horizontal pull exertions were recorded. Because of the lack of statistical difference between the left and right hands, these data were combined in the subsequent regression analyses.

The following equations were derived for the free standing and sitting trials:

Free Standing Posture: $Y' = -0.56X_1 - 0.31X_2 + 126.3$

Sitting Posture: $Y' = -0.30X_1 - 0.38X_2 + 94.6$

In these equations, Y' is the predicted horizontal pulling force expressed as a percentage of absolute pulling force exerted at the 1070mm height (220mm height in the sitting trials) at the midline of the body; X_1 is the vertical distance from the floor (or seated reference position in the sitting trials) expressed as a percentage of stature (or sitting height), and X_2 is the horizontal distance from the mid-line of the body expressed as a percentage of one half of the lateral span (measured with fists closed).

When normalized to these linear anthropometric data, the standardized residuals of the regression displayed a normal distribution in both the free standing and seated data sets, indicating that the original data does not violate the assumption of normalcy. This further illustrates that even within a small range of anthropometric measures, strength expression can be quite variable given the experimental set-up. Both equations were found to be statistically significant ($p<0.001$) and had correlation coefficients of 0.73 and 0.80 for the free standing and sitting trials respectively. In comparison with the original input data, the mean prediction error was less than 5% for both data sets. The undesirable location of a lever, control or load is often the description given of a poorly designed workstation or task. In this regard, expression of experimental data in absolute measures provides a better data set for Ergonomists to examine existing task conditions. However, the representation of these data in relative measures may allow for easier generalisation to other populations and assist in the design of more optimal workstations with greater regard for subject morphology. A larger sample size would further improve upon the statistical stability and thus the interpretation of these data and certainly would be necessary to use such data types to develop industrial guidelines for this manual materials handling activity.

3.5 Conclusions

Measurement of these pull forces in one direction were collected because of limited instrumentation and resources available to the investigator at the time of data collection. Notwithstanding this recognized limitation in the data set, these results are still considered useful for two reasons. Firstly, a data set reflecting any horizontally directed pull forces about diverse locations in the frontal plane cannot be easily found in the ergonomics literature, in spite of the assumption that this is a commonly executed manual materials handling activity. Secondly, in developing countries where less than desirable workstations are still likely to exist, it is just as probable that similar technologies would be used to perform workstation assessments. Thus, this benchmark data would be of some utility to Ergonomists performing on-site evaluations of manual materials tasks requiring horizontal pull exertions.

Results from this study suggest that the location of levers, handles or heavy manual materials within a frontal plane will influence the magnitude of an operator's horizontal isometric pull force in the sagittal plane. This suggests that the design of workstations in the frontal plane should account for the variability in operator strengths, even within a limited range of anthropometries. The workspace should also be designed to allow the operator freedom to assume postures that promote stability and leverage advantages.

While the findings from this study are consistent with some of the previous literature on the topic (Chaffin *et al.*, 1983; Daams, 1993), this study is novel in that is presents previously unreported information about horizontal isometric pull strength decrements associated with exertions created at more extreme reach envelope locations. These data suggest that overexertion injuries are more likely if an operator is required to exert maximal efforts at the vertical and/or horizontal extremes of a reach envelope, due to a reduced capacity for strength expression. In both the free standing and sitting postures, for example, strength deficits of over 60% were observed between differing locations within a frontal plane reach envelope. Controlling for operator location relative to the load can be regarded as an important design strategy for workstations requiring pull force exertions.

Chapter 4
A Psychophysical Approach to Determining Self-selected Movement Frequencies for an Upper-Body Pulling Activity

While pulling activities have been the focus of much manual materials handling research, little data exists which describes the psychophysically acceptable workloads which can be attempted during single-handed, submaximal, repetitive exertions. This information is important for the design of workstations and necessary to develop adequate work to rest ratios in tasks that require continuous pulling activities. It was revealed that there is a non-linear decrease in the frequency of pulling as the load is increased between 10 and 30 kg in 5 kg increments. Subjects perceived that the self-selected pulling frequencies chosen during a 20 minute experimental protocol could be endured for a typical full workday. The variability in load, normalised to subject mass, and the pulling frequencies increases over relative loads of 28% body mass and pulling frequencies of 12 per minute, respectively. It is recommended that protocols that employ values over these limits be used with caution, as the rate of onset of fatigue may be increased at higher load conditions, even though there is a concomitant decrease in pulling frequency.

4.1 Introduction

Manual materials handling occupations often require an operator to exert repetitive, submaximal pulling forces (Baril-Gingras and Lortie, 1995). These authors indicated that in a warehouse setting, for example, over 50% of handling activities require some level of force exertion in the horizontal plane. In the past several years, ergonomists have advocated the reduction, if not elimination through workstation re-design or appropriate administrative controls, of heavy lifting tasks, due to their relationship to low back pain (Resnick and Chaffin, 1995) as well as other musculo-skeletal injuries. As a result, lifting and lowering activities are generally limited to infrequent manipulations, although the loads might be relatively heavy. Pulling activities, however, often require light loads being handled more frequently. The frequent occurrence of pulling activities has been linked to musculoskeletal injuries (Hoozemans *et al.*, 1998) although this evidence tends to be more anecdotal in nature, rather than from evidence which identifies biomechanical or physiological mechanisms related to the injury. Thus, more research is required to identify how often and in what manner loads are manipulated by an operator employing a pulling action.

In an occupational context, operators are often required to perform a volume of work throughout the workday. This workload is a product of load magnitude and the frequency at which it is handled. Maintaining stable, acceptable levels of work output should reduce the onset of operator fatigue or discomfort (Datta *et al.*, 1979) over the extended workday. Often the load and pace of work are governed by the manufacturing process, therefore, changes in the production rate would require management intervention. However, if a piecework situation exists then the operator is free to choose a pace in which to make repetitive exertions and how long or frequent work breaks should occur, as long as production goals are achieved.

Considerable research has examined the relationship of maximal allowable lifting limits and their relationship to lifting frequency (Karwowski and Yates, 1986; Mital, 1987). However, little attention has been given to this relationship for pulling actions. Obviously the relationship between load magnitude and frequency of exertion in pulling activities is going to be different than those of lifting and lowering activities. Ciriello and Snook (1983) found that the psychophysical technique, often used in the development of safe and acceptable lifting guidelines, overestimated forces and maximum acceptable weights for tasks occurring at very high frequencies. Karwowski and Yates (1986) suggested that the psychophysical approach should not be used to set standards for lifting activities occurring at frequencies greater than 6 lifts.min^{-1}. Whether this suggested upper limit is correct for activities other than lifting has not been explored, particularly for pulling activities.

The majority of the research which has focused on pulling actions have examined maximal exertions (Ayoub and McDaniel, 1974; Warwick *et al.*, 1980; Kumar, 1994; Mital *et al.*, 1995; MacKinnon, 1998) under a variety of different experimental and industrial conditions. However, submaximal, repetitive work seems to be more reflective of *in situ* industrial demands. Snook and his colleagues (Ciriello *et al.*, 1990; Snook and Ciriello, 1991) have established acceptable workloads for a variety of pulling conditions. Because these researchers employed a cart/treadmill experimental set-up, these pull forces were generated primarily through exertions by the lower body. Because lower segment musculature tends to be large and powerful, applying these pulling load guidelines to more gracile, upper body musculature is likely inappropriate. To the authors' knowledge, there have been no studies which have published acceptable or safe workloads for the upper body musculature performing repetitive, submaximal pulling tasks.

The objective of this study is to examine the relationship between load magnitude and preferred frequency of exertion during a repetitive, single-handed pulling activity. An understanding of what type of workloads or movement frequencies are safe for upper body pulling exertions is necessary. Researchers in occupational ergonomics must approach future research which employ reasonable workloads/ volumes in their experimental designs. Not only will this make laboratory-based guidelines for acceptable practices more applicable to the industrial situation, but will also facilitate the comparison of future research works. It is hypothesised that the relationship between pull load and frequency will not be linear in nature. Similar methodological approaches considered in lifting exertions (Mital, 1983) demonstrated a non-linear relationship between load and exertion frequency.

4.2 Methods

Subjects

14 subjects (9 males and 5 females), free of any acute or chronic orthopaedic maladies, volunteered to participate in this study. All subjects were Human Kinetic and Ergonomics students enrolled at the University at the time of data collection. Following a demonstration of the experimental protocol and a verbal description of the requirements for participation in the study, written consent was obtained from each subject. Standard anthropometric characteristics of these subjects are summarised in Table 4.1. The methods in which elbow height and forward reach measurements were recorded are described in Pheasant (1988). Subjects were instructed to refrain from eating, smoking, drinking caffeine-containing beverages and engaging in moderate to vigorous physical activity for at least 3 hours prior to any data collection session. For most subjects, data collection occurred over a two to three day period, with a minimum of 1 hour of seated recovery between trials.

Table 4.1: Subject characteristics.

	Age (years)	**Mass (kg)**	**Stature (mm)**	**Elbow Ht. (mm)**	**Reach (mm)**
mean	22.43	71.30	1773.50	1105.71	615.43
sd	1.74	14.42	105.77	62.41	37.74
max	27.00	106.00	1913.00	1185.00	680.00
min	20.00	43.00	1584.00	1009.00	560.00
cv	7.76	20.22	5.96	5.64	6.10

Equipment

A Challenger isoinertial pulley system (Zest Manufacturing, Steenberg, South Africa) was employed to provide a horizontal resistance against which the subject would exert a concentric-eccentric pulling action. The subject was aligned in front of the pulley system so that the handle of the isoinertial machine was located in a horizontal plane coincident with the subject's elbow height. A platform, with a surface area of 600 mm by 600 mm, in which the vertical height could be adjusted was used to align the subject to the desired height. The location of the subject away from the origin of the pull was established in the following manner. The subject was asked to place their feet together, in a symmetrical fashion while grasping the handle of the isoinertial machine. The subject was then asked to step backwards, until the feet were the distance of the extended arm away from the handle of the pulley system. The platform used to adjust the vertical elevation of the subject was then positioned so that the geometric centre of the platform's surface area was below the feet of the subject.

Procedure

A psychophysical-based methodology was employed to determine the self-selected pulling frequency for various experimental loads (10, 15, 20, 25 and 30 kg). Each subjects was told to "imagine you are employed in a piece work industry where you get paid for the amount of work that you complete in a day. However, you must work an 8-hour day and therefore must adopt a pace which will allow you to complete the shift and return home without undue strain or excessive fatigue." These instructions are similar to those employed by Garg and Saxena (1979) and Zhu and Zhang (1990). The research personnel throughout the data collection period gave no external motivation.

The subjects were allowed to select a pulling frequency for each randomly presented load condition. All exertions were single-handed pulls employing the subject's self-selected dominant hand. The subjects pulled at a self-selected frequency for a duration of 20 minutes. Thus, pull frequency measures were the dependent measures in this experiment. Load order was randomised for each subject. For each minute the cumulative number of pulls and the heart rate were recorded using a hand-held counter and a Polar heart rate monitor (Polar Electro Oy, Kempele, Finland). The mean pulling frequency and heart rate were calculated from the minute-by-minute data for each load condition for each subject.

Throughout the duration of each trial, the subjects were free to move their feet, although the feet could not leave the confines of the surface area of the platform. The experimenter ensured that the pull was made in a horizontal direction and that the subjects pulled through a full range of motion. For each pull action, the hand was required to displace no less than 320mm from the location of the origin of the pull. A visual cue on the isoinertial machine was used to assist the subject with this requirement. This experimental task was selected to represent common activities observed in industries such as fishing (*e.g.* deck-side traps and nets), construction (*e.g.* cables through conduit) and manufacturing (*e.g.* mechanical-lift assisted power tools).

Four subjects were randomly selected to repeat randomly chosen experimental conditions. Each of these subjects repeated two of the load profiles one week after the initial experimental collection. For these data, a repeated measures t-test was employed to assess subject reliability. There was no significant difference (p = 0.18) between the repeated measures. The mean relative difference ([initial – repeat]/initial*100%) between the initial data collection and the repeated measure was 12.8%.

4.3 Results and Discussion

Introduction

For most subjects and conditions, the data from the first minute of each trial were extremely variable compared to the rest of the time-series data. It became obvious to the investigators that this interval was used by the subject to acclimatise to the trial, in order to select a pulling frequency that could be endured for an extended period of time. Therefore it was decided to eliminate the first minute of data for all trials and subjects and subsequent analyses are based upon nineteen minutes of continuous data for each subject during each load condition.

Much of the comparative literature referred to in this paper is sourced from research on lifting activities. This is due to the fact that very little published research on upper body pulling tasks exist which employ a psychophysical approach to examine frequency and workload characteristics. While trends in this experimental data seem to be consistent with the reviewed lifting literature, the similarities may simply be due to chance, as muscular recruitment and perhaps even the approach to a pulling task may be different than lifting tasks.

From Table 4.1 it can be seen that there is a large variability in the mass characteristics of the subjects (coefficient of variation = 20.2% and range = 63 kg) employed in this study. An attempt was made to recruit subjects of diverse masses which would also presume a large range of strength capabilities. In this regard, three female subjects perceived they could not endure the 30 kg condition for twenty minutes, although all three subjects could manipulate the load in multiple, single repeat attempts during familiarization trials. However, as a result of several pre-pilot studies, it was assumed that pulling loads between 10 and 30kg would be typical of a manual materials handling setting, and thus, suitable values for this experimental protocol. Debriefing discussions with those female subjects who reported they could not endure the highest load condition revealed that although they could manipulate the load infrequently, which might be assumed to be a frequency of less than 1 exertion per minute, none considered it to be a load suitable for regular occupational exposure. Future experimenters may want to reduce the higher range of load demands or be more selective during subject recruitment, utilizing participants who possess strength capacities or vocational experiences typical of *in situ* operators.

Heart Rate Responses

Table 4.2 reports the average heart rate values for all subjects for each load condition. A repeated measures ANOVA revealed no significant differences in the subject's heart rate across the five load conditions (p=0.5625).

Table 4.2: Average heart rate values (standard deviation) across load conditions.

Load	**10kg**	**15kg**	**20kg**	**25kg**	**30kg**
Average	87.6	95.1	92.3	92.1	88.4
(sd)	(14.5)	(18.9)	(14.1)	(11.5)	(12.9)

Heart rate response can serve as a valuable indicator of physiological stress, especially if no confounding environmental or psychological factors exist (which is believed to be the case for this particular study). Zhu and Zhang (1990) report that the general consensus in the literature is that under normal occupational circumstances, healthy operators should be able to tolerate an upper heart rate limit of 115 beats.min^{-1} over an 8-hour workday. While some subjects in this study may have had heart rates exceeding 115 beats.min^{-1} within or throughout a condition, on average, the heart rates never exceeded this value. Upon initial examination of the physiological data, it is assumed that the subjects in this experiment indeed selected reasonable and consistent pulling frequencies, or workload, for each condition, that could be possibly endured for an 8-hour work period. Mital (1987) observed a decrease in heart rate of industrial workers (1.9% per hour) and student subjects (1.1% per hour) during lifting tasks that lasted over 8 hours (with scheduled rests and lunch breaks). Therefore, it could be assumed that the heart rates observed in this study would be near task maximum values, if the tasks were to continue longer than the defined experimental protocol.

Subject Regulation of Pulling Frequency

Figure 4.1 represents the group mean (and standard deviation) frequency of pulling for each load condition. These data are represented as the complete data set, as well as the segregated male and female data. A repeated measures ANOVA revealed that there were significant differences ($p < 0.0001$) across the load conditions for each of the data sets. However, a Scheffe F-test *post hoc* paired condition analysis indicated that there was no significant difference between the 20kg - 25kg and the 25kg - 30kg conditions for the group, male and female profiles. As a group, the females exerted significantly ($p = 0.047$) smaller pulling frequencies than the males performing the same task.

It must be recognised that the subjects in this study selected a pulling frequency based on a concentric - eccentric movement pattern. While this type of pulling action may be common to a variety of manual materials handling tasks (Resnick and Chaffin, 1995), recommendations from this study must be limited to this cyclical form of motion. In a situation, such as slag removal, when an operator releases a load after pulling it towards the body, one would expect that the metabolic demands would be lower than a comparable load in which a concentric-eccentric pulling action occurred. This certainly would have an impact on the load-frequency relationship as derived by psychophysical means as well as the physiological costs reflected by the heart rate profiles. It could be hypothesised that for a concentric-only pull, the frequency would increase for each experimental load. However, this assumption has not been tested.

Mital (1987) questioned the validity of utilising student volunteers for research attempting to address industry-specific situations. Whilst student subjects are desirable from a recruitment convenience perspective, they may lack the vocational experience to perform certain manual materials handling tasks in a learned, efficient manner or may even have different morphologies to actual industrial workers. Mital (1987) did acknowledge that research that examines data trends may take some liberties with subject selection, however, the magnitudes of the observed experimental factors must be questioned if employed *in situ*.

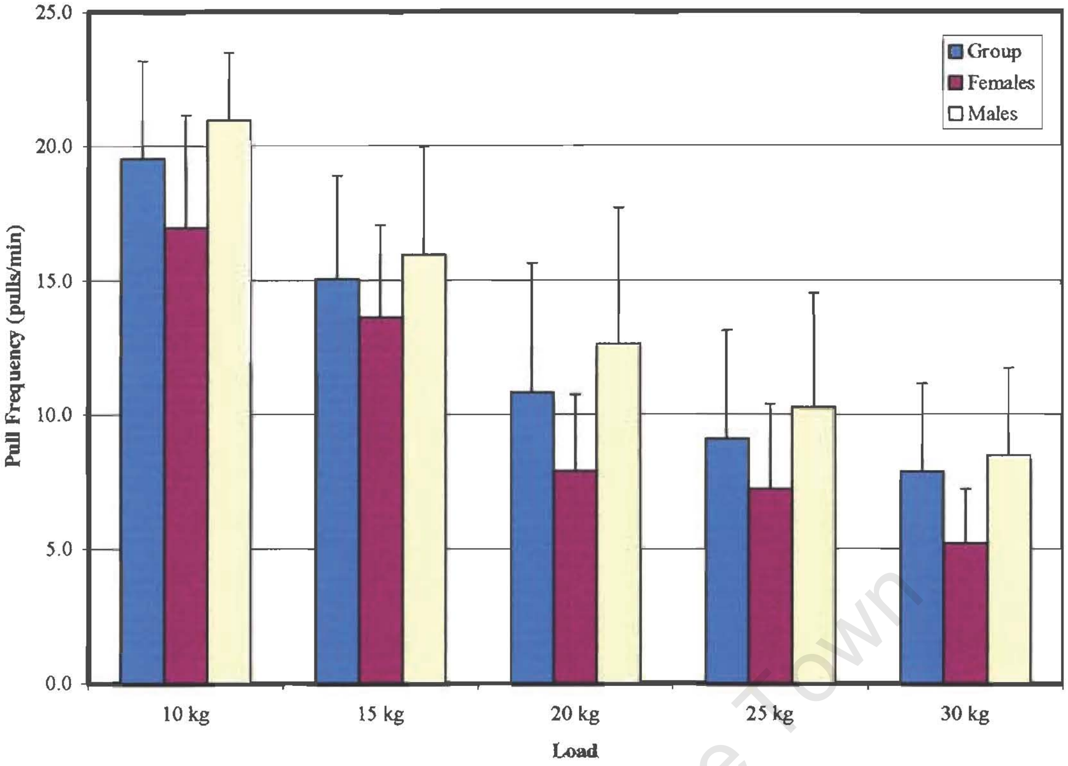


Figure 4.1: Mean pulling frequency versus load condition.

Magnitude of Resultant Workload

Efficiency and productivity can often be two opposing factors with respect to the level of operator safety (Zhu and Zhang, 1990). In an industrial setting, an operator is expected to maximise output (*i.e.* workload) but must work at a capacity that will not precipitate injury or poor performance. The primary goal of this research was to gain some insight into the manner in which subjects control the frequency of pulling actions.

A repeated measures ANOVA was employed to assess whether the absolute volume of work per minute (*i.e.* load x average frequency of pulling per minute) was consistent across conditions for each subject. The volume of work for an individual subject across conditions was found not to be significantly different (p=0.2469). However, there was a significant difference in the volume of work performed between subjects, regardless of the load condition ($p < .0001$). The average volume of work performed over all the experimental conditions ranged from 87 kg.min^{-1} to 448 kg.min^{-1}. Given the large mass differences in the subjects, it should be expected that the absolute volume of work per minute would be different for each subject.

Because the absolute magnitude of workload per minute was different between subjects, these data were normalised to assess whether there was a relative difference between the volume of work performed by each subject. The total volume of work per minute was divided by the subject's mass, thereby normalising workload to body mass. Still there was a significant difference in the volume of work as a proportion of body mass manipulated per minute between subjects ($p < .0011$). The average relative volume of work performed per minute over all the experimental conditions ranged from 1.31 times body mass to 5.56 times body mass. Differences in the relative workload per minute across subjects are not as easily explained as the differences in absolute workloads. Such large inter-subject variability in relative workload values may be due to the differences in the subject's level of cardiovascular or musculoskeletal conditioning. Perhaps some subjects employ similar pulling-type strength exercises as part of a conditioning programme, which would give them a certain advantage over subjects less familiar with the activity. The advantages of task familiarity to the efficiency of movement should not be underestimated.

Extrapolating data collected over a short duration (*i.e.* < 30 minutes) to a full workday (*i.e.* > 8 hours) must be done with caution. Mital (1983) found that lifting workloads selected as acceptable in the initial experimental stages, of a 12-hour protocol, were found to decrease as the experiment progressed. He suggested that adjustments should be made to data collected over shorter intervals. In this respect, pulling frequencies and workload magnitudes reported in this study should be considered the upper limits of a manual materials handling task of this nature.

Relationship between load and pulling frequency

A logarithmic fit ($r = 0.745$) was used to describe the relationship between pulling frequency and load handled. This provides an equation of $y = -11.045\ln(x) + 44.762$ to predict pulling frequency from an absolute load (see Figure 4.2). In order to assess the effects of subject mass on this prediction, the load data were expressed as a percentage of the subject's absolute mass.

Initially, these data were considered in three groups: the complete data set; those subjects who could complete all the experimental conditions (which necessitated the exclusion of the data for the three female subjects who could not complete the 30kg load); and only data from male subjects. Table 4.3 reviews the coefficients of determinations calculated as a result of submitting these sets through various regression analysis fitting routines. Eliminating the data from the female subjects who could not complete the 30kg load created a better regression fit compared to the regressions performed on the complete data set. In all cases, a logarithmic fit best described the relationship between relative load and pulling frequency.

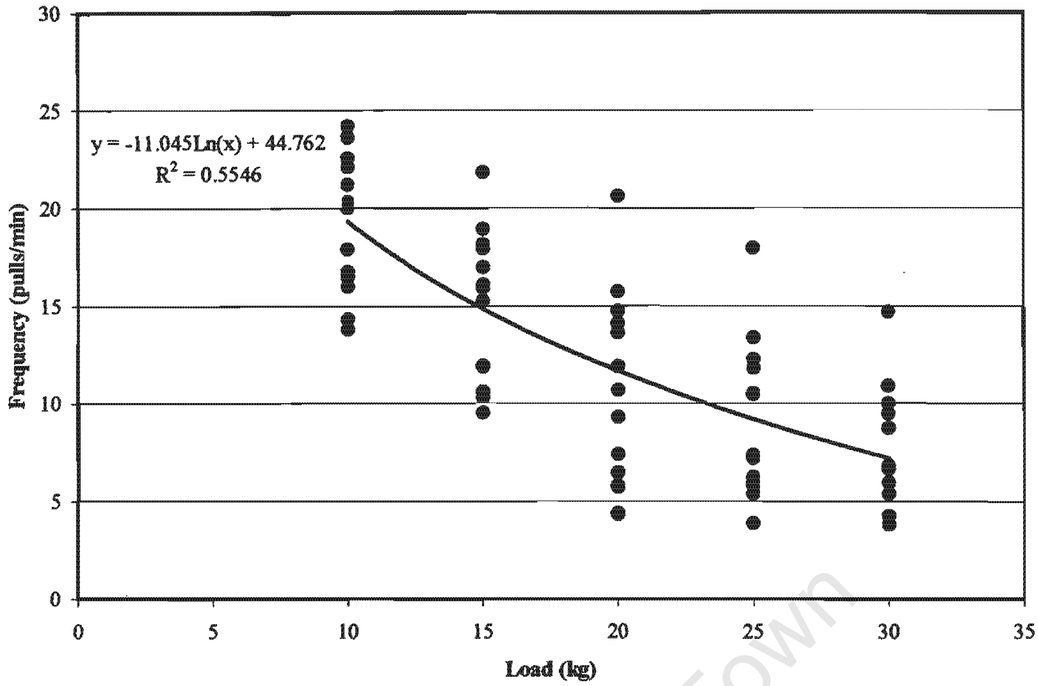


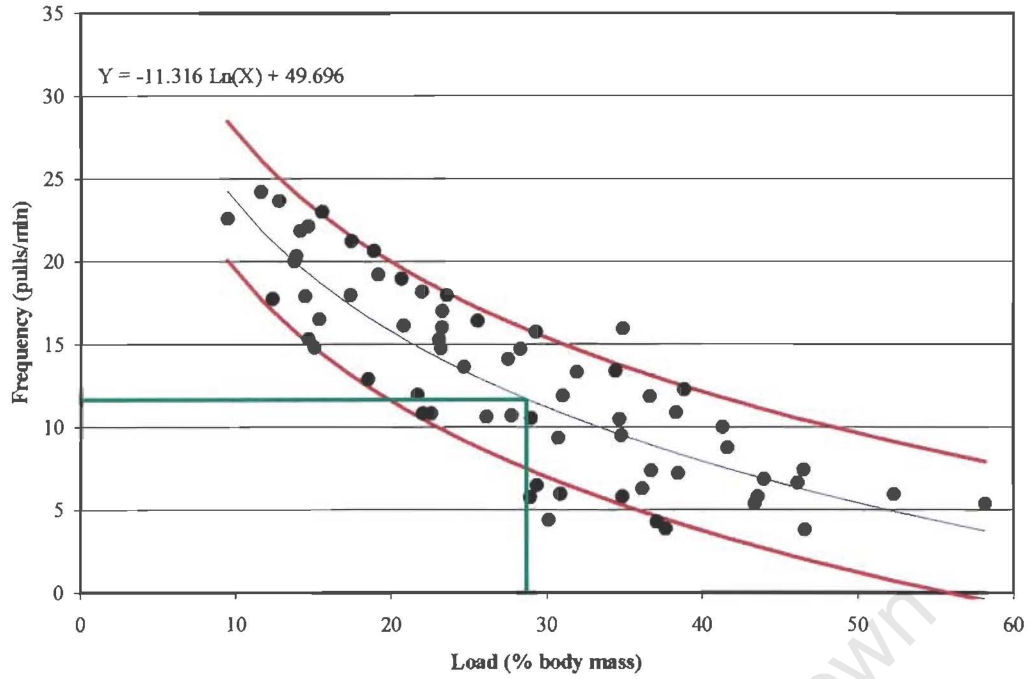
Figure 4.2: Regression plot of pulling frequency and absolute load.

The most prominent observation is that the variability of the data across the range of loads normalised to subject mass is not consistent. Figure 4.3 depicts the regression of relative load (% body mass) against pulling frequency (pulls/min). Figure 4.3(A) represents the regression plot for all subjects, while Figure 4.3(B) represents the regression plot for all subjects who completed the entire experimental protocol. In order to assess the consistency of the variability, lines indicating the boundaries of one standard deviation above and below the line of best fit are included. Figure 4.3(A) reveals that workloads that either use loads over 28% of body mass (author's estimation represented by a green vertical line) and/or pulling frequencies over 12 per minute (represented by a green horizontal line) may result in more variable performances than smaller load and frequency combinations. The nature of this variability may be due to a greater propensity towards fatigue at higher pulling frequencies or the inability of the smaller upper body muscles to efficiently manipulate loads of these magnitudes. Figure 4.3(B) was produced in a similar fashion to Figure 4.3(A), except the data from the three subjects unable to complete the full protocol (*i.e.* the 30kg load) were eliminated from the regression analysis. It becomes apparent that the variability in these data is reduced and a majority of those data points falling outside of the ± 1 standard deviation are removed. Examination of those remaining points lying outside the ± 1 standard deviation are, in most part, distributed among different subjects, and cannot be attributed entirely to the remaining female subject data included in this regression analysis. It may be a coincidence, or perhaps given the manner is which the data were reduced an inevitable mathematical outcome, that 20kg equals 28.05% of the average mass of the subjects (71.30kg). Figure 4.2 reveals that the range in pulling frequencies for the data set is greatest for the 20kg load and remains high for the 25kg load. While the 30kg load does not continue with this trend, this can be likely attributed to the missing data from three of the female subjects. While magnitude of load handled will be the most likely factor for injury in maximal or near-maximal exertions, assessment of performance stability (*i.e.* variability in the dependent measures) may provide some insight towards a better determination of acceptable limits for submaximal, repetitive activities by a psychophysical model.

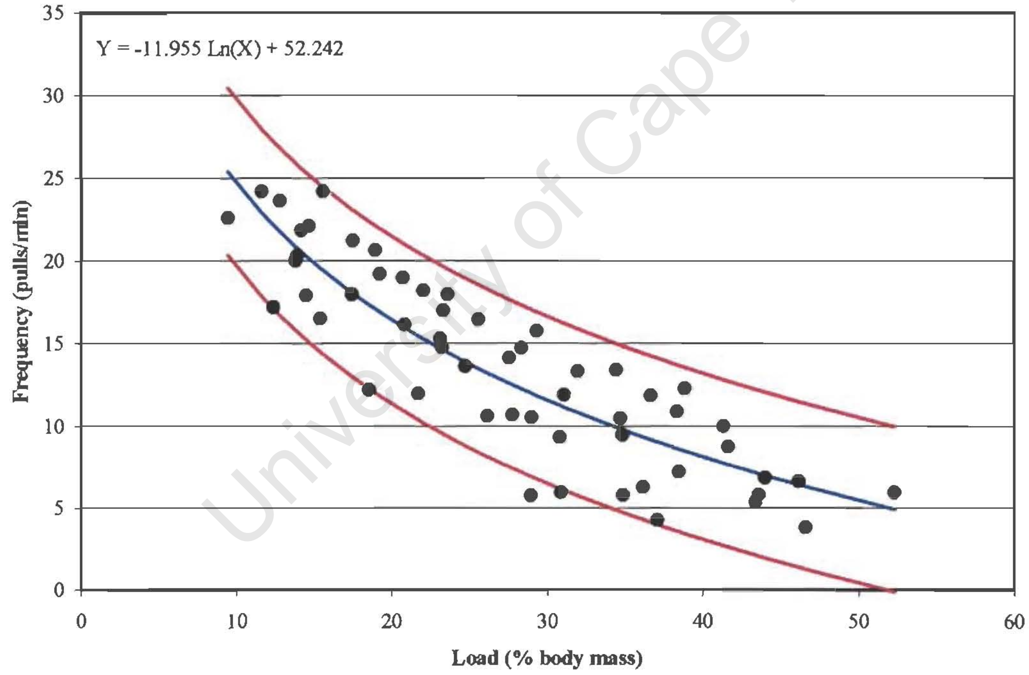
	2nd Order Fit	3rd Order Fit	Log Fit	Linear Fit
All Subjects	0.689	0.694	0.694	0.654
Subjects Who Completed Each Condition	0.766	0.774	0.775	0.755
Male Subjects	0.756	0.765	0.766	0.740

Table 4.3: R^2 values reflecting various regression fits between load (% body mass) and frequency (pulls/min) for the complete data sets, those subjects completing all experimental conditions and male subjects only.

Resnick and Chaffin (1995) suggested that more basic research of the mechanisms influential in the psychophysical perceptions of exertions is required. They suggested that perhaps loads relative to an individual's maximum capacity should be examined. In this experiment, loads relative to the subjects body mass seemed to be a promising independent factor. However, the association between relative pulling load and frequency decays in relative loads greater than 28% of gross body mass or for pulling frequencies greater than 10 or 11 pulls.min^{-1}.



A. Complete Data Set



B. Subjects Completing All Load Conditions

Figure 4.3: Regression of relative load (% body mass) against pulling frequency (pulls/min). Figure 4.3(A) represents the regression plot for all subjects; Figure 4.3(B) represents the regression plot for all subjects who completed the entire experimental protocol; the blue lines represent the line of best fit; the red lines represent one standard deviation above and below the line of best fit.

4.4 Conclusions

Many of the observations from this study were supported by parametric statistics derived from a sample of 14 or less subjects. The main thrust of this paper was to provide some insight to the characteristics of repetitive, upper body pulling activities, as well as, provide some solutions to methodological problems. However, a sample of this size does not necessarily allow for generalised statements regarding pulling guidelines applicable to industry.

Subjects were not necessarily experienced manual materials handlers and might not have employed effective movement strategies to complete the experimental protocol. Future research should assess the general impact of this methodological limitation and determine the validity and reliability of extrapolating a 20-minute protocol of single-handed pulling to that performed over a complete workday.

Each subject altered the frequency of pulling with a change in load but maintained a reasonably constant volume of work throughout the five randomised load conditions. This reveals some consistency in the manner that a subject psychophysically selects a work pace. This is further supported by the intra-subject stability of the heart rate responses across conditions. However, for a given load, the volume of work within a given period is significantly influenced by the mass, and thus absolute strength, of a specific subject.

A decrease in pulling frequency with an increase in load was to be expected, as the subjects were instructed to choose a workload which each perceived could be sustained for a full workday. This volume of work, across load conditions, must be related to the resistance to whole-body and localised fatigue of the subject performing this task. While the load was increased systematically by 5kg, the decrease in pulling frequencies where not linear.

There are very few conclusive, quantifiable means of assessing the relationship between fatigue and self-selected rate of work. Some have advocated the use of electromyographical (EMG) analysis to assess the level of localized neurological fatigue (Dolan *et al.*, 1995). While subjects in this study may have reported that a chosen pulling frequency was acceptable for a full day's work, collection of EMG data to assess shifts in the EMG power spectrum would have provided corroborative neurophysiological support to these subjects' perceptions. It may be desirable to collect EMG data in future experimentation to assess the validity of the psychophysical approach to guideline development of upper body pulling tasks.

Chapter 5

Effects of Standardized Foot Positions During the Execution of a Submaximal Pulling Task

This study examined how experimentally controlled foot positions could affect the temporal and spatial parameters of a load (20% of subject mass) during a one-handed repetitive submaximal pulling activity. Foot positions standardized relative to a frontal and sagittal plane defining a pull force vector were derived based on the preferences of 45 volunteer subjects. In general, the subjects assumed asymmetrical foot positions and on average the big toe of the foot contralateral to the hand exerting the pull was located 19% (SD = 4.4%) of stature in front of the frontal plane containing the pull origin and 8.6% (SD = 4.5%) of stature laterally from the sagittal plane through which the load was displaced. The big toe of the foot ipsilateral to the hand exerting the force was located at a distance of 46.7% (SD = 6.3%) of stature in front of the frontal plane containing the pull origin and 0.4% (SD = 3.9%) of stature laterally from the sagittal plane through which the load was displaced. The left and right feet were orientated at angles of 56.8° (SD = 20.2°) and 25.9° (SD = 22.7°), respectively, relative to a right horizontal of a frontal plane parallel to the plane containing the origin of pull. These foot positions were subsequently employed in a second experiment to investigate how dictating foot positions would affect the way in which 15 newly recruited subjects exerted a pull force on the same load. Results from this experiment showed that the load velocities and forces were not affected by standardized foot positions when compared to those collected when subjects were free to choose foot orientations. It is suggested that future researchers should consider the benefits of employing standardized foot positions in studies of pull exertions, particularly for methodologies similar to that described in this study.

5.1 Introduction

With the introduction of assistive devices for manual materials handling (MMH) activities and improvements in the conditions of work due to sound ergonomic intervention strategies the physical demands due to lifting upon an operator in industry are being systematically reduced. For various reasons, these changes have resulted in increased demands for operators to exert pull forces at the worksite (Baril-Gingras and Lortie, 1995; Koningsveld and van der Molen, 1997). However, compared to lifting, the ergonomics of pulling has received less attention by researchers and little is known about the manner in which operators create such forces and how this relates to musculoskeletal injuries (van der Beek *et al.*, 1999).

Operator posture and pertinent workstation parameters will affect the manner in which a task is performed (Haslegrave *et al.*, 1997). With respect to executing pulls, the manner in which an operator positions the feet within a stationary workstation not only has an effect on the expression of strength, but also has certain safety implications (Grieve, 1983). To date, persons investigating pull forces have either chosen to allow subjects to freely select how the feet are placed or have systematically standardized these positions during experimental protocols. This has made comparison of the results between studies difficult. However, the extent to which these different methodological approaches influence the outcome of the dependent measures has not been adequately studied. Such information may provide the needed insight to decide upon appropriate methodological constraints in the future.

Ayoub and McDaniel (1974) suggested that foot position was critical for biomechanical efficiency in creating a maximal two-handed pull force. They found that the force increased as the subject positioned the leading foot closer to the frontal plane that included the origin of the pull. In fact, when the foot went beyond this frontal plane by 10% of standing reach height, the pull force was further increased. Warwick *et al.* (1980) examined a series of left-, right- and two-handed pulls while the feet were fixed in five different symmetrical and asymmetrical foot orientations. While no statistical analyses were reported, tabular data suggests that foot position influenced the magnitude of maximal pull forces, regardless of how the hands were employed. MacKinnon (1998) found that imposing foot orientation had a statistically significant effect on the ability to produce maximal isometric pull efforts about various locations in the frontal plane. Subjects pulled on a strain gauge while the feet were in a fixed, symmetrical position and when the foot positions were freely chosen. Dictating foot positions decreased the maximal pulling force by an average of 36% (with a maximum within condition of 48%) when compared to freely chosen foot orientations.

Conversely, for various pulling heights and one- and two-handed pulls, Chaffin *et al.* (1983) found no difference in maximal isometric pulling strength when the feet were positioned symmetrically or when subjects were free to choose preferred asymmetrical foot positions. However, it should be noted that in a series of silhouettes included in the paper that represent typical postures chosen by the subjects, none represented a forward foot position beyond the frontal plane at which the location of the force occurred, an orientation that was found to be desirable by Ayoub and McDaniel (1974) to create a maximal pull force. Whether Chaffin *et al.* (1983)

restricted subjects from selecting more forward foot positions or whether there were physical restrictions in the experimental set-up was not indicated in the report of the methodology.

Daams (1993) conducted a study that examined maximal isometric one-handed pulls. This was a two-part experiment, in which she first compared the pull forces created under three postures: a subject-chosen posture; a position in which the body was perpendicular to the force measurement device; and an asymmetrical position relative to the force measurement device, where the opposite foot to the hand exerting the force was placed in front. The forces were exerted at shoulder and elbow heights. At both heights, there was a significant increase in the pulling force using the free posture, on average twice as large as in the two fixed postures. While she believed that free postures would be better related to *in situ* demands, she acknowledged that this experimental approach presented a limitation for those attempting to reproduce the study or for those who wished to extrapolate the data for other purposes. In the second part of the experiment she compared the free posture data with a 'functional' posture where the position of the hands and feet were fixed but the rest of the body was free to assume any orientation. This posture prescription does provide an element of standardization for future experimental protocols. Again, the maximal isometric forces produced for the free posture were greater than for the functional posture, but what proved more interesting was that the reproducibility of the postures by subjects between repeated measures were similar in the 'free' and 'functional' postures. Fixing the body parts that transferred force to the outside world in the second phase of the experiment did not seem to affect the manner in which the task was executed by the subject, but it did decrease the magnitude of the maximal pull force, independent of the height of pull.

While freely chosen postures seem to improve the production of pulling forces under maximal isometric attempts, the effects of foot posture have not been systematically investigated for dynamic pulling events. These pulling actions are more typical of fixed workstations. Owing to improvements in technology there has been a concomitant increase in the number of experimental protocols examining dynamic pulling actions. Dynamic pulling studies include the use of isokinetic devices (Kumar, 1995a; Kumar *et al.*, 1995) or isoinertial systems in order to create a resistance against the operator. However, to date, these research designs seem to be more concerned with examining the changes in muscle mechanics rather than postural influences on the execution of pulling activities.

Other researchers have undertaken investigations of pulling tasks under submaximal load conditions (Lortie and Baril-Gingras, 1988; MacKinnon, 1999) as these levels of exertions are more typical of industrial demands. While optimal foot postures contribute to how pull strength is maximized, these will also influence the execution of pull tasks at submaximal loads. In experimental designs employing submaximal exertions, the loads are typically controlled as independent variables while other task or operator factors are assessed. In such experimental designs, foot posture may require some form of standardization. Values chosen for standardization purposes must not be so prescriptive that the natural manner in which an operator performs the activity is compromised, but must be sufficiently stringent to enhance inter-trial, subject and condition, comparisons. If a standardized methodology for dictating foot positions for standing pulling activities could be developed, the opportunities for an investigator to make comparisons to other similar literature would be improved and the modelling demands of kinetic analyses satisfied.

It is obvious that foot positions play an important role in the expression of pulling strength and require further attention regarding the extent to which this variable should be controlled in experimental designs (Haslegrave *et al.,* 1997). Previous researchers have promoted the use of a 'free' or subject-selected posture for future experimental protocols in order to maintain more realistic, task-related protocols (Grieve and Pheasant, 1981; Pheasant *et al.,* 1982; Daams 1993). Contrary to this perspective, Warwick *et al.* (1980) advocated strict control of body postures, including foot placements, and the employment of a modeling approach to estimate *in situ* postures and demands. While this approach may limit how the data may be generalized, it does provide the necessary methodological control typically needed to assess changes in the dependent experimental variables. Both methodological approaches have obvious advantages and disadvantages.

The purpose of the present study was two-fold. First, it was designed to investigate the 'typical' foot orientations which subjects adopt when attempting single-handed, submaximal pull forces under isoinertial loading and whether these foot orientations could be described in terms of subject morphology and/or workstation parameters. The second purpose of this study was to determine whether imposing these standardized foot positions would affect performance of a pulling task compared to the same task performed when subjects were free to select their own foot orientations. Changes in task performance were assessed by examining the differences in load kinematics between experimental conditions. Defining foot positions for studies of pulling activities will only be meaningful if the standardization procedure does not significantly affect the manner in which subjects would normally perform the task.

5.2 Methodology

This experiment was conducted in two phases. The first phase of the experiment consisted of the collection of subjects' freely chosen foot positions while attempting submaximal pulls resisted by an isoinertial load. Specific anatomical locations of the left and right feet were recorded in a horizontal plane and were measured to define these as a proportion of the subject's stature relative to the frontal and sagittal planes defining the origin and direction of the pull force at the initiation of the exertion. These data were summarized and used to define standardized foot positions for the second phase of the experiment. Forty-five subjects volunteered to participate in the first phase of the study. All were reported to be physically healthy and free of injury and all reported right-hand dominance. Their details are given in Table 5.1.

Table 5.1: Subject anthropometrics for both phases of study.

		Age (Years)	**Mass** (kg)	**Stature** (mm)	**Elbow Height*** (mm)
PHASE 1					
ALL SUBJECTS	Mean	20.2	69.6	1727.6	1078.2
(n= 45)	SD	1.8	11.5	89.3	79.0
	CV	8.8	16.5	5.2	7.3
FEMALES	Mean	19.6	60.7	1656.7	1057.2
(n= 22)	SD	2.2	5.2	49.9	99.4
	CV	11.4	8.5	3.0	9.4
MALES	Mean	20.8	78.1	1795.3	1098.3
(n= 23)	SD	1.1	9.1	61.1	46.6
	CV	5.2	11.6	3.4	4.2
PHASE 2					
ALL SUBJECTS	Mean	21.4	68.8	1716.4	1044.6
(n= 15)	SD	5.0	8.3	75.5	45.2
	CV	23.4	12.1	4.4	4.3

* - distance of lateral epicondyle from floor; SD = standard deviation; CV = coefficient of variation.

In the second phase of the experiment, a sample of convenience consisting of 15 newly recruited male subjects were asked to perform similar submaximal pulls with two foot positions: freely chosen foot positions (free condition) and foot positions which were standardized based on the information collected in the first phase of the experiment (fixed condition). Subjects were screened for right-hand dominance and a preference for placing the left foot in front of the right foot when producing a single-handed pull. Table 5.1 also contains the summary anthropometric data for the subjects in this phase of the study.

In both phases of the experiment, written informed consent was given prior to the commencement of data collection and the subjects were provided with an opportunity to ask questions concerning the experimental protocol. The study was approved by the Human Kinetics and Ergonomics Ethics Committee.

Phase 1: Protocol to establish standardized foot positions

Prior to data collection, subjects from a student population were asked to attend a familiarization session, during which time anthropometric data were collected and screening occurred to identify those subjects who chose to place the right foot in front of the left foot while attempting a right-handed pull. Owing to this screening process, 1 male and 4 females were excluded from participation. The decision to eliminate these subjects was based on the fact that maximal forces are best created when the left foot is in front for right-handed pull attempts (Daams, 1993). A left foot forward posture seems to be an appropriate compensatory movement to a reach forward by the right upper segment (similar to movement patterns observed during bipedal locomotion) and positions the centre of gravity in a more optimum position within the base of support. Subjects who preferred a posture with the right foot in front would presumably have different segment co-ordination strategies compared to those with a posture with the left foot in front. Consequently, a subject pool of 45 subjects (23 males and 22 females) was tested in the first phase of the experiment.

A load situated on a pulley system that allowed for adjustments in handle height (En-tree, Enraf Nonius BV, Holland) provided the horizontal resistance. The En-tree system collects time series load displacement data via a system of potentiometers measuring cable excursion. The system's proprietary software employed a finite differences technique to calculate load velocity and applied force.

The vertical height of the origin of pull was positioned at the subject's elbow height and the load resistance was set at 20% of the subject's absolute body mass. The subject was asked to exert a pull force which was in the horizontal plane coincident with the elbow joint and in a parasagittal plane that included the subject's glenohumeral joint. The subject was told that this task represented an industrial activity and that he or she should estimate a rate and magnitude of force of exertion that would enable him or her to continue the repetitive task comfortably over a full work day. After several minutes of familiarization with the task, which included 25 to 50 repeated force exertions and self-exploration of various unshod foot positions, the subject was asked to select what he or she considered to be the most comfortable and efficient positions of their feet to perform the pull. The supporting surface was constructed of wood and covered with coarse newsprint. At no time during the data collection did any subject complain of instability under foot. An outline of each foot was traced on the supporting surface and the following points on each foot were demarcated: the most distal aspect of the big toe, the medial aspect of the 1st metatarsal, the lateral aspect of the 5th metatarsal and the central aspect of the posterior calcaneous. The location of the frontal plane containing the origin of pull and the parasagittal plane indicating the direction of pull were also recorded.

Phase 2: Comparison of free and standardized foot positions

This phase of the experiment was undertaken to determine whether the foot positions described from the results of the first phase of the study would affect the manner in which the subject executed a pull force on a load when assuming freely chosen foot positions.

All 15 subjects completed 10 consecutive right-handed concentric-eccentric pulling motions for each of the free and fixed foot conditions. The same isoinertial pulley system employed in phase 1 of the experiment was used to apply a resistance to the subject. The load was set at 20% of the subject's absolute mass and the direction of pull was the same as defined in phase 1 of the experiment.

Conditions were presented in a set order to each subject, free foot positions first and fixed foot positions second. This was done in order to eliminate any bias that might have occurred from knowing how the fixed foot conditions were orientated. Any bias due to a learning effect was considered negligible due to the habituation period all subjects had previously undergone, so that randomization of the conditions was deemed to be unnecessary. For the free condition, the subject assumed a self-selected foot position. The positions of the unshod feet were traced and the anatomical landmarks were marked on the paper upon which the subject stood prior to commencing the 10 pulling actions. In the free condition, the distance that the load was displaced was not constrained. For the fixed position, the investigator aligned the feet of the subject, using the orientations determined in the first phase of the experiment, and instructed the subject to exert 10 pull repetitions, displacing the load to a specified distance demarcated on the rail upon which the load moved.

5.3 Results

Phase 1: Preferred location of feet relative to origin of pull

Figure 5.1 illustrates the system that defines the linear co-ordinates and angular orientations of the long axis of the foot. Foot angle was described as the angle between the frontal plane and the line joining the central aspect of the posterior calcaneous and the most distal aspect of the big toe. Table 5.2 includes a summary of the mean distances depicted in Figure 5.1. These data are reported as mean absolute values as well as values normalized (indicated by a superscripted 'n' in Table 5.2) to subject stature.

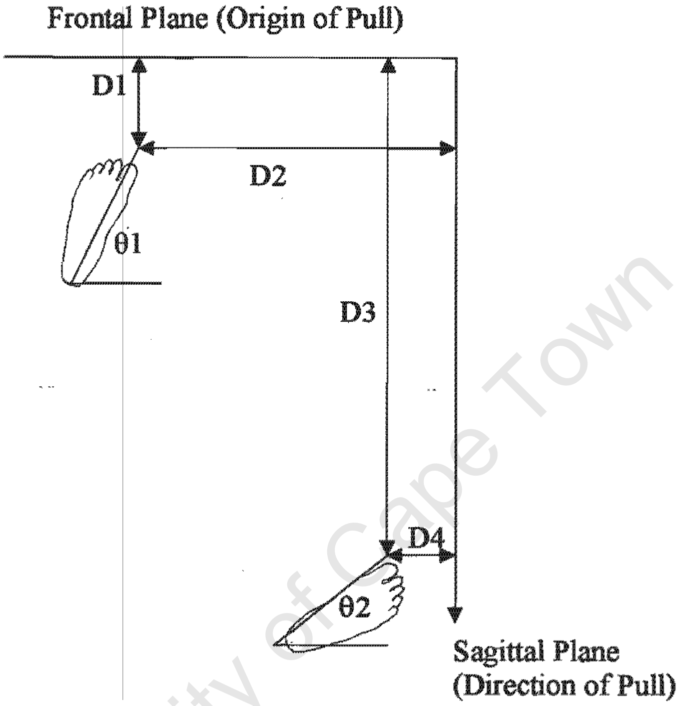
A series of independent t-tests revealed no statistical differences between the male and female subjects for any of the absolute distances depicted in Figure 5.1, except for D4 (Table 5.2). However, the absolute difference in the male and female means for this parameter was small (46 mm). Therefore, it was decided to pool the female and male data in order to derive more robust standard foot positions that would be suitable for a larger range of subject morphologies.

Table 5.2 also includes the angular orientations of the feet for the group of subjects (using the dimensions defined in Figure 5.1). Similar to the foot landmark distances, independent t-tests revealed no statistical differences between the male and female subjects for both angular orientations.

Table 5.2: Summary of foot landmark positions (absolute and relative) with respect to the origin of pull. (Dimensions are as shown in Figure 5.1.)

	D1 (mm)	**$D1^n$ (%)**	**D2 (mm)**	**$D2^n$ (%)**	**D3 (mm)**	**$D3^n$ (%)**	**D4 (mm)**	**$D4^n$ (%)**	**$\theta 1$ (°)**	**$\theta 2$ (°)**
mean	327.0	19.0	148.3	8.6	805.7	46.7	6.1	0.4	56.8	25.9
SD	74.1	4.4	76.7	4.5	114.4	6.3	65.1	3.9	20.2	22.7
CV	22.7	23.0	51.7	52.5	14.2	13.6	1059.8	940.6	35.5	87.8

Note: linear values denoted with a subscript 'n' have been normalised to subject stature.



Where:

D1 and D3 are the distances of the most distal aspects of the left and right big toes, respectively, to the frontal plane containing the origin of pull.

D2 and D4 are the distances of the most distal aspects of the left and right big toes, respectively, to the parasagittal plane through which the pull is exerted.

θ1 and θ2 are the included angles between the vectors describing the central aspects of the left and right posterior calcanei and the most distal aspects of the left and right big toes, respectively, from the right horizontal.

Figure 5.1: Overhead view of system defining location of foot landmarks relative to the origin of pull.

Load displacement for Phase 1 of experiment

The vertical excursion of the load, which equates to the horizontal pull distance, was recorded. Once the foot positions had been traced on the supporting surface, the subject was requested to exert continuous, repetitive pulls, but to pause briefly between the concentric-eccentric cycles. There was no significant difference in the mean pull distance between males and females (mean = 771mm, SD = 163mm; mean = 700mm, SD = 136mm, respectively). The mean (and SD) absolute pull distance for all subjects combined was 735 (152) mm and the mean (and SD) pull distance normalized to subject stature was 42.7 (8.4) % of stature.

Derivation of standard foot positions from Phase 1 of experiment

It is interesting to note that very little association ($r = 0.01$) existed between stature and horizontal pull distance even though the subjects were free to choose foot positions at any distance from the frontal plane that included the origin of the pull. It might be expected that taller subjects would have longer upper limbs and therefore a greater absolute horizontal excursion of the hand in such a task, compared to a smaller subject. However, this appeared not to be the case.

The purpose of the first phase of the experiment was to ascertain whether the subjects demonstrated similar spatial orientations of the feet while engaged in a one-handed submaximal pulling action under isoinertial loading, which could be used to characterize a condition for standardizing foot positions. The results in Table 5.2 suggest that the left toe should be positioned a distance of 20% of stature from the frontal plane of origin of pull (Dl) and a distance of 10% stature from the sagittal plane containing the line of pull (D2). The left foot should be angled so it is pointing to the right at an angle of 55° relative to a frontal plane parallel to the plane containing the origin of pull (θl). The right toe should be positioned at a distance of 45% of stature from the frontal plane of the origin of pull (D3) and on the sagittal plane containing the line of pull (D4). The right foot should be pointing to the right at an angle of 25° relative to a frontal plane parallel to the plane containing the origin of pull ($\theta 2$). Even though there seemed to be no relationship between subject morphology and absolute pulling distance, it was decided to standardize the distances relative to stature, in case future studies employ subjects of extreme stature. These values have been rounded slightly from those originally suggested in Table 5.2. This was done to simplify the positioning of the subject during the second phase of the experiment.

Independent t-tests revealed no significant difference in mass, stature and elbow height between the subjects employed in the two phases of the study (as shown in Table 5.1).

In order to assess whether there were differences in how a person performed a pulling action between fixed and free foot positions several aspects of the collected data were selected for statistical and graphical analyses. Two main differences were addressed: whether the load kinematics were affected due to foot posture and whether the spatial parameters of the free foot positions chosen by the subjects differed from the prescribed fixed foot positions.

Twelve temporal and spatial characteristics of the load kinematics were extracted from each pull cycle and averaged over the 10 repeated pulls for each subject for each condition. The results are given in Table 5.3. The mean values were then tested for differences using a repeated measures t-test. Significant differences (at 95% confidence) were found only for the concentric, eccentric and total movement times. In all cases, the movement time was greater in the fixed condition. This is probably due to the fact that in the fixed foot position the subject was required to pull to a specified distance. To ensure proper targeting, the subject would probably have slowed down the speed of pull, particularly near to the end of the exertion, thus increasing movement time. Maximum and mean velocity and force values were determined for both the concentric and eccentric movement phases. Velocities were slightly faster for the free foot condition (but there were no statistically significant differences).

Data used in the statistical analyses were acquired prior to employing a normalization technique to average time-series data. All time-series data were normalized to 100% movement time using a second-order polynomial fit. Normalized data for the trials were averaged at intervals of 1% of the movement time. Figure 5.2 provides a comparison of the velocity-time profiles for the fixed and free foot conditions. Figure 5.2(a) represents the author's selection of a subject who demonstrated little difference in the average load velocities between the free and fixed conditions. Figure 5.2(b) illustrates, in the author's opinion, the subject who demonstrated the greatest variance in the averaged load velocities between conditions. Figure 5.2(c) represents the average of all fixed and free velocity profiles for all experimental subjects.

A comparison of freely-selected foot positions with the fixed foot positions revealed almost no statistically significant differences (Table 5.4). The only spatial difference was found for variable Dl, where subjects in the second phase of the experiment seemed to favour a closer foot location to the frontal plane containing the point of application of the pull force.

Table 5.3: Comparison of mean (standard deviation) load kinematics between fixed and free foot positions.

Variable	**Fixed Positions**	**Free Positions**	
Distanced Pulled (m)	0.701 (0.078)	0.734 (0.155)	
Concentric Movement Time (s)	1.22 (0.29)	1.11 (0.24)	*
Eccentric Movement Time (s)	1.61 (0.39)	1.46 (0.27)	*
Total Movement Time (s)	2.83 (0.62)	2.56 (0.46)	*
Maximum Concentric Velocity ($m.s^{-1}$)	1.13 (0.30)	1.25 (0.35)	
Mean Concentric Velocity ($m.s^{-1}$)	0.60 (0.13)	0.68 (0.18)	
Maximum Eccentric Velocity ($m.s^{-1}$)	0.81 (0.22)	0.92 (0.26)	
Mean Eccentric Velocity ($m.s^{-1}$)	0.46 (0.10)	0.52 (0.13)	
Maximum Concentric Force (N)	191.4 (30.3)	201.5 (42.5)	
Mean Concentric Force (N)	136.3 (14.8)	136.0 (15.1)	
Maximum Eccentric Force (N)	168.3 (19.0)	170.1 (23.6)	
Mean Eccentric Force (N)	136.2 (14.7)	136.6 (14.3)	

* denotes significant difference at $\alpha = 0.05$

Stance area, considered to be the size of the base of support defined by the locations of the big toes and posterior aspects of the calcanei, was calculated employing Bretschneider's formula (Beyer, 1978). A repeated measures t-test revealed no significant differences between the stance areas for the fixed (mean = 0.095 m^2, SD = 0.013 m^2) and free foot (mean = 0.093m^2, SD = 0.017 m^2) positions examined in phase 2 of the experiment.

5.4 Discussion

Laboratory-based experiments, while often lacking the realism of field testing, do provide the advantage of more rigorous experimental control. In studies of pulling activities, there has been much debate as to the extent to which foot positions should be controlled. If the purpose of an experiment is to investigate the maximal forces a subject can generate, then the feet may be positioned at the discretion of the subject. However, if the purpose of a study is to compare, for example, spinal kinematics between subjects or if a methodology requires precise kinematic

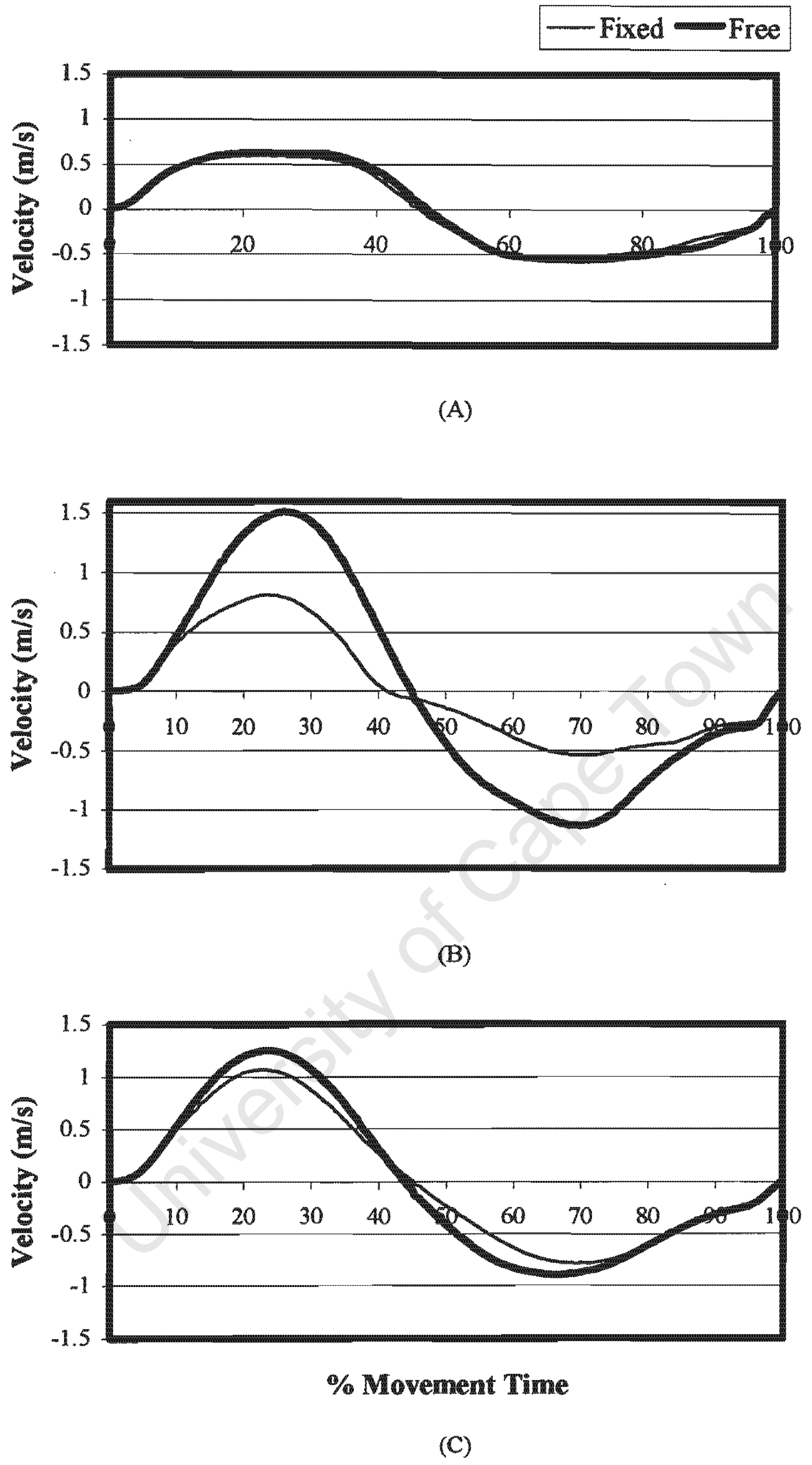


Figure 5.2: Comparison of averaged load velocity-time profiles of the fixed and free foot positions for the most repeatable (a) and least repeatable (b) subjects between conditions. Figure 5.2(c) represents the averaged velocity-time series across all subjects for the fixed and free foot positions.

Table 5.4: Comparison of mean (standard deviation) foot locations between fixed and free foot positions (refer to Figure 5.1).

	$D1^n$	$D2^n$	$D3^n$	$D4^n$	$\theta 1$	$\theta 2$
	(% stature)	(% stature)	(% stature)	(% stature)	(°)	(°)
Mean	16*	8.7	43.4	(-)1.3 **	59.7	24.5
SD	3	4.1	5.2	3.9	15.7	16.6
Fixed	*20*	*10*	*45*	*0*	*55*	*25*

* denotes significant difference at $\alpha = 0.05$

** a negative (-) sign indicates that the mean location of the right big toe was to the right of the sagittal plane containing the direction of pull.

measurements for the purpose of resolving internal forces or moments, then the orientation and measurement of foot positions must be strictly controlled. While several studies have examined the effects of foot position on pull strength expression, no study to date has specifically suggested guidelines for standardizing this variable and whether such a standardizing procedure would have a confounding effect upon the collection of submaximal pull force profiles. The results from this study suggest that dictating foot positions in such a manner prescribed in phase 1 of the study had no real pertinent effect on load kinematics collected in phase 2 of the study.

The 'functional posture' for pulling at elbow height as described by Daams (1993) was remarkably similar to the standardized dimensions proposed in this study, even though subjects exerted maximal isometric forces and had the right foot in front of the left. She proposed that the lead foot should be placed 20% of stature and the posterior foot 48% of stature from the frontal plane containing the origin of pull. Although Daams found that the variability in producing repeated maximal forces was similar between the functional and free postures, the functional posture produced lower maximum isometric forces in comparison to the free posture. These differences in maximal force might be expected, particularly under isometric conditions, because it is likely that any prescribed posture will be less than optimal for a given individual. However, this situation is of less concern in submaximal, dynamic exertions. Under dynamic conditions a subject has a greater degree of freedom to co-ordinate various body segments as compared to isometric conditions. A subject's ability to choose different movement strategies under dynamic conditions could override the effects of less than desirable fixed foot positions and in the process enable the operator to exert greater and more repeatable pull forces.

Chaffin *et al.* (1983) found that subjects tended to prefer asymmetrical foot positions during maximal isometric pull exertions, choosing to place the left foot in front of the right foot, and suggested that this posture would allow a subject to more easily regain balance in the case of a slip. However, the foot positions which they described were considerably closer to the frontal plane containing the origin of pull than those observed in the present study. Interestingly, they found no statistical differences in the magnitudes of isometric pull forces between the symmetrical and asymmetrical foot positions. It is also interesting to note that the reported one-handed mean pull strength values were similar to those measured in the present study. This suggests that perhaps the distance the operator stood from the frontal plane may have not orientated the subject so as to maximize isometric force output or highlight the advantage of dynamic exertions, particularly when the inertial properties of the upper body segments can be exploited to contribute to the forces applied to the load.

It is acknowledged that a right foot in front of left foot orientation may have some relevance to actual occupational demands and perhaps exclusion of subjects demonstrating this postural approach should be reconsidered in future studies. However, given the task demands (i.e. load magnitude and displacement) selected for this study, a fixed right foot in front of left foot orientation would likely require greater amounts of trunk axial rotation in order to displace the load and is inherently less stable than a left foot in front of right foot orientation, as the centre of pressure would be located behind the right foot for a significant portion of the pull cycle. Perhaps future studies should focus explicitly on determining the advantages of a right foot in front of left foot orientation; this posture may be related to improvement in load control.

Haslegrave *et al.* (1997) discussed the methodological implications of foot positions in examining maximal one-handed isometric force exertions in awkward working postures. They chose only to fix the forward foot and positioned this relative to the origin of pull. In all cases, these foot positions were closer to the origin of pull than those employed in the present study. The maximal isometric pull forces that Haslegrave *et al.* (1997) reported were generally smaller than the maximal forces reported for submaximal loads in the present study. While this might be a function of the closer foot positions, it probably reflects the profound effect that awkward postures have on the expression of strength.

It is difficult to compare foot postures for pulling tasks that call for maximal isometric exertions and those requiring submaximal dynamic activations. The demands are so very different and it is likely that the strategies employed by the operator to position the feet under these circumstances are different. In exerting maximal forces, it is likely that the operator will choose foot positions that contribute to maximizing the force couple between the feet and hand, while for submaximal dynamic pulls the operator might be expected to establish foot patterns that aid in maintaining dynamic equilibrium. This strategy becomes even more important as the speed of pull increases and the rate at which the centre of pressure travels in the posterior direction through the base of support increases.

The differences in the velocity curves depicted in Figure 5.2 for free and fixed foot positions are small, even for the subject considered to have the greatest differences between the free and fixed conditions (Figure 5.2(b)). More importantly, the shapes of the sinusoidal-like profiles are very similar, suggesting that fixing foot positions affect neither temporal nor spatial parameters. It is important to assess trends in time-based information, even if only in a subjective manner, as practical differences can be overlooked if employing only maximum, minimum or averaged data within analyses.

While it is important that the prescribed foot positions do not affect load kinematics it is also important that the posture imposed on the subject could be typical of a self-selected posture. Table 5.4 indicates that the way in which the subjects positioned their feet in the freely chosen posture was not significantly different from the spatial orientations recorded in the first phase of the experiment. Only Dl, the distance of the left big toe from the frontal plane containing the point of application at the start of the pull, was statistically significantly different between the two conditions. Selecting positions closer to the frontal plane with the left foot has been shown to be advantageous in creating maximal isometric forces (Ayoub and McDaniel, 1974). However, in absolute terms, the average difference between the location of the left big toe from the frontal plane containing the origin of pull between the fixed and free conditions was only 69.1 mm (i.e. 4% of mean subject height), which seemed not to be a large enough difference to affect the measured load kinematic and kinetic profiles. While Chaffin *et al.* (1983) reported that even small constraints upon posture can affect the forces produced by an operator, it seems that employing the foot positions identified in phase 1 of this paper does not induce a significant experimental effect upon the majority of the dependent variables, including mean and maximum pull forces (as shown in Table 5.3).

It is acknowledged that the prescribed foot orientations considered in these findings would not be sufficiently robust for the study of the plethora of industrial tasks for which pull exertions are required. These recommendations may only be suitable for experimental protocols using similar load magnitudes, displacements and pull force vectors. Heavy or maximal loads, for example, might require a larger base of support to assist in the development of larger pull forces and larger load displacement or more rapid production of force in the horizontal direction might require movement of the feet during the execution of the pull. Delisle *et al.* (1999) identified typical footstep patterns in common lifting and lowering manual materials handling tasks. Whether experienced operators develop strategies to optimize the size and location of the base of support to facilitate more efficient pulling actions requires further investigation. Furthermore, conditions under foot were ideal in this methodological approach. Pulling strategies and intra- and inter-subject variability would likely be affected for lower coefficients of friction between the foot and floor. Nonetheless, findings of this study support the use of standardizing foot positions as a suitable approach when developing methodological strategies to study pull force exertions.

More research is required to understand better the importance of foot function during pulling tasks, as the manner in which an operator creates and maintains the interface between the feet and the ground is important for both efficiency of movement and management of risk for slips and acute accidents. It is recommended that future studies address how the pull vector origin and direction, as well as load magnitudes, impact upon the movement control strategies an operator employs to exert horizontally-directed forces and the role of foot positions in influencing these movement outcomes. Examination of pull exertions employing isoinertial load conditions will require collection of operator kinematic-time profiles. Submaximal loads likely afford an operator more freedom in choosing how to perform the task.

5.5 Conclusions

Diverse experimental protocols are probably the greatest limitation to comparing existing research on pulling activities. Position of the feet during a pulling exertion is an experimental variable often controlled, but confirmation of whether this methodological decision has any significant impact upon dependent variables such as load kinematics has not been forthcoming.

Outcomes from the first phase of the experiment suggested that subjects chose reasonably similar characteristics in their base of support when attempting a submaximal isoinertial pull of 20% body mass. This spatial information was summarized to describe a method of standardizing foot positions relative to subject stature during submaximal pulls at elbow height. Phase 2 of the experiment confirmed that there were no real differences in load kinematics between freely-chosen and standardized foot positions so that foot postures may be adequately controlled for experimental protocols examining submaximal pulling activities similar to those in this study. This finding is particularly pertinent for those studies that wish to control the hand-foot force couple variables while investigating kinematic and kinetic profiles of other body segments during dynamic pulling activities.

Chapter 6

Spine Kinematics Associated with Submaximal One-Handed Pulling Exertions

Pulling exertions are a common form of manual materials handling yet little is known about the manner in which an operator exerts a submaximal force in a horizontal direction, particularly when attempting exertions about diverse locations in the frontal plane. This study examined the load and spine kinematics of 20 subjects for various pulling tasks. These tasks included three load conditions (6%, 12% and 18% lean body mass) and four pull origins described in anthropometric terms relative to the frontal and sagittal planes. These findings suggest that a subject will tend to increase the magnitude of the angular velocity and acceleration for both back extension (33 to 141 deg.s^{-1} and 129 to 539 deg.s^{-2} respectively) and axial rotation (42 to 76 deg.s^{-1} and 139 to 276 deg.s^{-2} respectively) in order to accommodate the demands of increased pull loads. However, only back extension kinematics were altered with changes in pull origin, although some exertions were attempted at a location considerably lateral to the anatomical sagittal plane. Magnitudes of angular velocities and accelerations were found to be comparable to those observed for lifting tasks considered to place an operator at high risk for low back disorders. It is concluded that repetitive, submaximal pull exertions such as those examined in this study may predispose an operator to risk of overuse injuries because of the considerable dynamic motions required of the trunk, and such handle orientations should be avoided in workstation design particularly if coupled with heavy pull loads.

6.1 Introduction

Ergonomic intervention strategies over the past decades have focused on the reduction of manual materials handling (MMH) activities such as lifting, lowering and carrying in hopes of reducing the incidence of work-related injury, with a particular focus on low back pain (NIOSH, 1981). Therefore it would not be surprising that the occurrence of pushing and pulling activities has increased as a consequence of the introduction of ergogenic aids or alterations of task demands to reduce the demands of lifting, lowering and carrying (Koningsveld and van der Molen, 1997; Hoozemans *et al.*, 2000). Baril-Gingras and Lortie (1995) found that nearly half of the MMH activities in a warehouse setting to be characterised as pushes or pulls. This finding emphasizes the need for a better understanding of the strategies operators employ to produce horizontal forces, and elucidation of the potential negative outcomes of repeated submaximal exertions.

Unlike lifting, lowering and carrying, which use similar muscular groups under varying conditions of neuromuscular activation, pulling and pushing exertions exhibit very different musculo-skeletal dynamics and should thus be considered as distinct MMH activities. It is not sufficient to simply consider, collectively, exertions in a horizontal plane. It is essential that researchers dichotomize between pulling and pushing activities in order to gain a better understanding of the mechanisms and types of injuries resulting from repeated exposure to these motions. In this respect, this study will focus on the execution of pulling exertions.

Much of the research into pulling exertions has focused on the limitations of workstation and/or operator morphology on the execution of maximal exertions. In general, this literature has reported that for single-handed exertions, pull height origins should be at about the operator's elbow height (Chaffin *et al.*, 1983; Daams, 1993) and that maximal pull force strength capabilities decrease as the pull origin moves superiorly or inferiorly and laterally from this location (MacKinnon, 1998). While this research has provided valuable information relevant to tool and workstation design specifications, it is more likely that submaximal, repetitive pulling exertions are more typical of those employed *in situ*. Furthermore, there is very limited evidence which directly links strength to injury and therefore experimental methodologies employing repetitive, submaximal loading profiles are likely to provide more insight into demands imposed by cumulative loading.

Several researchers have examined the musculo-skeletal loading profiles on the operator as a result of pull motions (Kumar, 1994; Lee *et al.*, 1991) under varying workstation and postural conditions. Unfortunately, in order to derive such kinetic data, experimental conditions have to be rigorously controlled and can be highly subject to modelling errors, thus limiting the predictive validity of these models. While it is recognized that it is the system kinetics that are more directly related to specific injury mechanisms, research should perhaps focus less on predictive kinetic models and more on the significance of the kinematic characteristics of the motion (Imrhan and Ayoub, 1990). Marras *et al.* (1990) have suggested that measures such as displacement, velocity and acceleration could provide valuable insight into the strategies employed in dynamic motor performance.

The purpose of this study was to examine whether variations in workstation parameters and load magnitudes would affect lumbar spine kinematics of subjects exerting single-handed pulls originating from diverse locations in the frontal plane. Benchmark data documenting trunk kinematics should help Ergonomists to identify aspects of pull exertions that might predispose on operator to increased risk of acute and chronic low back injuries. It is hypothesized that as the pull location moves away from the sagittal and frontal planes, and as the pull load increases the magnitudes of the thoracolumbar kinematics, as measured by a lumbar motion monitor, will increase.

6.2 Methods

Participants

Twenty healthy adult males volunteered to participate in the study. Subjects reported no current or past musculoskeletal injuries and selection was limited to those who reported right hand and lower limb dominance.

After the experimental protocol was explained and the subject was offered an opportunity to ask questions, informed consent was obtained, as per guidelines established by the Ethics Committee. Subjects were then given an opportunity to attempt the pull tasks under approximated experimental conditions. Following this acclimatization period, the subject's anthropometric measurements were recorded (see Table 6.1). Detailed description of the anthropometric measurement procedures can be found in Pheasant (1988). Body density was estimated using the procedure described by Jackson and Pollock (1978) and percentage body fat was calculated by the Siri formula (Siri, 1956). Subjects were requested to return the following day to participate in the formal data collection session.

Table 6.1: Mean anthropometric data for 20 Subjects.

Variable	Mean	SD	CV	Min	Max
Age (Yrs)	22.0	2.0	9.2	19.0	26.0
Mass (kg)	83.3	12.4	14.9	65.4	114.6
Body Fat (%)	12.9	5.5	42.6	5.9	24.2
Lean Body Mass (kg)	72.0	7.6	10.5	60.1	86.9
Stature (mm)	1853.7	42.5	2.3	178.9	194.8
Elbow Height (mm)	1157.5	28.4	2.5	110.1	124.3
Eye Height (mm)	1735.8	46.8	2.7	167.3	182.5
Humerus Length (mm)	380.2	16.4	4.3	35.0	41.2
Shoulder Width (mm)	482.8	42.6	8.8	35.2	54.8
Hip Width (mm)	355.8	19.0	5.3	31.9	41.2

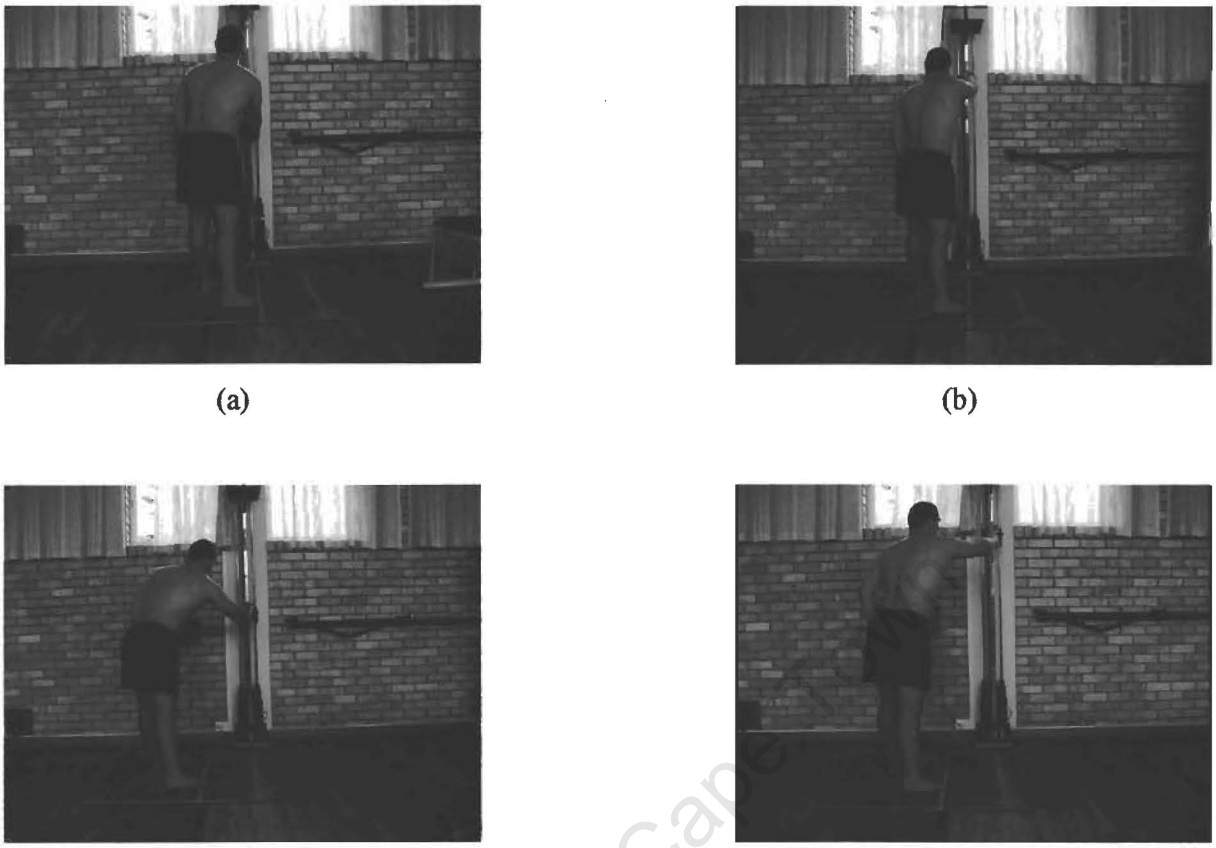
Experimental Task

This study examined one-handed pull exertions originating from four locations about the frontal plane. These pull origins were described within a standard planar system and were relative to the morphology of each subject. Two pull heights were tested - orbital height and elbow height - through two parasagittal planes. The sagittal planes occurred through the gleno-humeral joint centre when the arm was held relaxed at the subject's side and another plane lateral to this, at a distance defined by the length of the centre of the subject's gleno-humeral joint to the centre of the elbow joint. Figure 6.1 (a,b,c,d) illustrates these locations and for the remainder of the paper will be referred to as:

a. Elbow-In
b. Eye-In
c. Elbow-Out
d. Eye-Out

Each subject was required to exert these pulling actions against loads of 6, 12 and 18% of lean body mass. The magnitudes of these loads were based on suggestions made by MacKinnon (1999) and from extensive pilot work completed prior to commencement of the study. The subject was requested to maintain a grip on the handle attached to the load in a vertical orientation throughout the duration of each trial.

It was necessary to control several variables during the collection of the data. Foot placement was prescribed for each subject and kept constant for each experimental condition. The spatial orientation of each foot was controlled for each subject. The left big toe was positioned a distance of 20% of stature from the frontal plane of origin of pull and a distance of 10% stature from the sagittal plane containing the line of pull. The longitudinal axis of the left foot was orientated so it was 55 degrees relative to the right horizontal of a frontal plane parallel to the plane containing the origin of pull. The right big toe was positioned a distance of 45% of stature from the frontal plane of origin of pull and on the sagittal plane containing the line of pull. The longitudinal axis of the right foot was set at 35 degrees relative to the right horizontal of a frontal plane parallel to the plane containing origin of pull. These foot orientations are based upon recommendations by MacKinnon (2002). Subjects were asked to pull the handle in the horizontal plane a distance equivalent to 20% of their stature. A visual cue was clearly demarcated on the rail guiding the load excursion.



(a)

(b)

(c)

(d)

Figure 6.1: Location of pull origins: (a) Elbow height/sagittal plane dissecting gleno-humeral joint, referred to as "Elbow-In within text; (b) Eye height/sagittal plane dissecting gleno-humeral joint, referred to as "Eye-In within text; (c) Elbow height/sagittal plane located laterally, referred to as "Elbow-Out within text; and (d) Eye height/sagittal plane located laterally, referred to as "Eye-Out" within text.

In order to ensure the pull was executed in a horizontal plane, a freely hanging foam-padded target, with an auditory feedback mechanism, was appropriately positioned for each trial. Subjects were required to make contact with the foam pad with the dorsal aspect of the hand or the elbow at the end of each pull cycle. The foam target was lightweight and thought not to contain sufficient mass to influence the execution of the pull exertion.

Subjects were free to choose the tempo at which the pull cycles were executed, although subjects were encouraged to maintain temporal consistency within a particular condition. No auditory or visual prompt was given to the subject in this respect. The subject was requested to provide a discernible pause in between each movement cycle but not to hesitate in the transition between the pull and load-return phases.

Apparatus

An En-tree isoinertial pulley system (Enraf Nonius B.V., Holland) was employed to provide a horizontal resistance against which the subject exerted a pull and load-return action. The investigator could select loads in 0.5 kg increments. In order to expose the subject to the required 6, 12 and 18% lean body mass loads, an appropriate additional mass was secured to the top weight plate of the system. The height of the handle, attached to the load via a cable system, was adjustable to 20 mm intervals. The device measured load displacement via a series of potentiometers at a sampling frequency of 100 Hz and had a measurement resolution of 2 mm. Velocity-, and acceleration-time profiles were derived employing a finite differences algorithm contained in the software purchased with the device. Force- and power-time profiles were calculated from these data.

A Lumbar Motion Monitor (LMM) was employed to assess the three-dimensional thoracolumbar kinematics (Marras *et al.*, 1992). The LMM was attached to the subject by a harness system placed over the thorax and pelvis areas. Data were sampled at 60 Hz via an analogue-to-digital converter and transformed into angular positions using a regression model. Angular velocity- and acceleration-time profiles were calculated by numerical differentiation.

Experimental Procedure

A randomised block factorial design was employed in this study. Two independent variables were defined: (1) pull load and (2) location of pull force about the subject's position relative to the frontal plane.

The subject was asked to stand on a slip resistant surface that demarcated the standardised foot positions. The feet were then aligned to the investigator's satisfaction. As in the session during which anthropometric data were collected, the subject was provided ample time to familiarise himself with the data collection protocol and to attempt all conditions prior to actual data collection. Data collection did not commence until both subject and experimenter were satisfied that the subject could competently execute the task.

The subject was asked to exert approximately 10 pulls for each condition. Attempts were made to select five consecutive efforts for subsequent analysis. Five repeated measures have been reported to be sufficient to obtain an unbiased estimated of the demands imposed on the subject (van der Beek *et al.*, 1999).

Data from the LMM and the En-tree isoinertial pulley system were synchronised in time at the commencement of data collection for each trial. Selected pull cycles were identified by employing the displacement profiles measured by the En-tree unit. Subjects were given a minimum of 150 seconds of rest between each trial in order to minimise the effects of fatigue. Load and pull force locations were randomly presented to each subject in order to eliminate any order effects.

During the collection of these data, the electromyographical profiles from the left and right erector spinae, left and right external obliques, right trapezius, latissimus dorsi, deltoid and biceps brachii were also monitored. These data will be discussed in Chapter 7 of this dissertation.

Statistical Analyses

A two-factor analysis of variance for repeated measures was employed to assess the effect of load and pull location on the load kinematics and the LMM data. If a significant difference was detected for either of the main effects, the Scheffe *post hoc* analysis method was employed, and a 95% simultaneous confidence interval for specified linear combinations was used.

6.3 Results

Load Kinematics

There were no significant differences in the load displacements, pull times and peak and mean pull velocities between load and pull locations. The mean pull time and peak velocity for all cycles were 1.21 (+/- 0.01) seconds and 1.28 (+/- 0.05) $m.s^{-1}$ respectively.

As to be expected, there were significant differences for peak and mean pull forces ($p < 0.0001$ and $p < 0.0001$ respectively) and peak and mean pull powers ($p < 0.0001$ and $p < 0.0001$ respectively) between all load conditions but not between the four pull locations within a load condition. The mean peak forces for the 6, 12 and 18% loads were 67 (+/- 1) N, 123 (+/- 1) N and 183 (+/- 1) N respectively. The mean peak powers for the 6, 12 and 18% loads were 70 (+/- 1) W, 120 (+/- 1) W and 186 (+/- 1) W respectively.

Figure 6.2 includes representative profiles of the displacement, velocity and acceleration time-series data for side bending, flexion/extension and rotation of the spine as detected by the LMM.

Table 6.2 contains the start and finish orientation of the spine in all three movement directions while Table 6.3 contains the maximum displacement, velocity and acceleration values obtained for each condition relative to the movement directions.

Figure 6.3 depicts the mean magnitudes of variability, expressed as the coefficient of variation across subjects, for the start and finish positions (refer to Table 6.2) in the sagittal and twisting directions. For the starting orientation, there were significant differences in the amounts of variability between the Elbow- and Eye-In positions compared to the Elbow- and Eye-Out positions ($p = 0.042$) in the sagittal plane. There was also a significant difference in this variability due to load magnitude ($p = 0.038$) in the sagittal plane start orientations. Neither load nor pull position affected the magnitude of the variability in starting position for the twisting plane LMM positions. There were no significant effects on the LMM variability for the finish position in the sagittal plane. With respect to the twisting kinematics, there was no statistical differences in the finish position variability for the twisting plane due to the original pull locations, although a load effect was present ($p = 0.026$).

Table 6.4 indicates the levels of statistically significant differences for selected kinematic variables for the LMM data. Specifically, the spine kinematics were assessed on four main events: the starting and finishing LMM orientation in all three planes, the maximum displacement, velocity and acceleration values obtained in each direction in all three planes for the three pull loads and the four pull locations. Table 6.5 contains the results from the statistical analyses of the effects of load mass and pull location on the time of occurrence of peak values for selected lumbar motion monitor variable. Figure 6.4 illustrates how the load and handle location influenced when peak velocity and acceleration occurred in the LMM measurement for the sagittal and twisting planes.

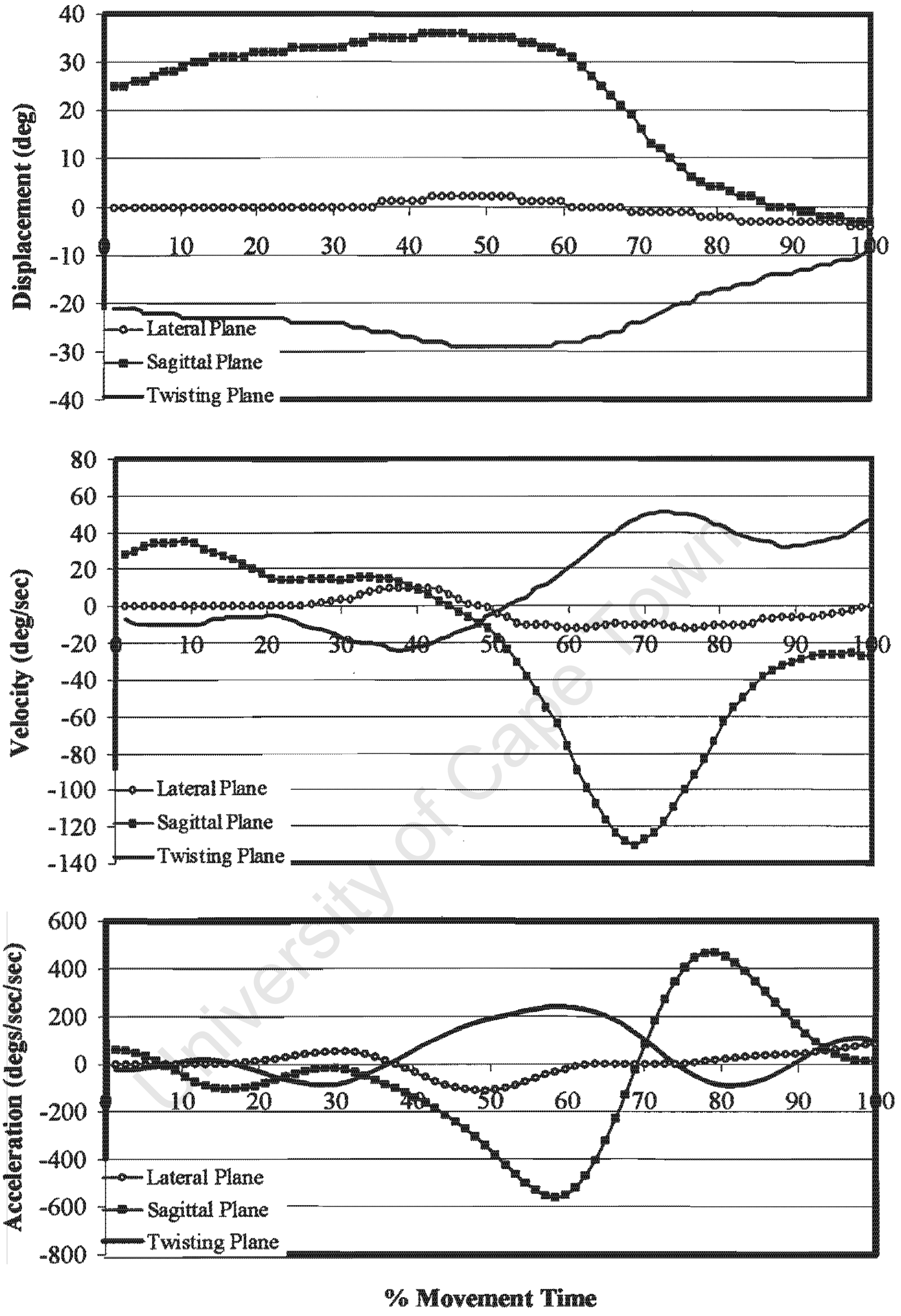


Figure 6.2: Representative kinematic profiles for all three planes during a pull cycle for one subject.

Table 6.2: Mean start and finish spine orientations in all three planes.

Start

Location	Mass	Bend Position (deg)	Flex/Ext Position (deg)	Rotate Position (deg)
Elbow-In	6%	1.4	16.5	-15.1
	12%	3.1	27.2	-19.2
	18%	-5.5	11.2	-16.1
Elbow-Out	6%	-3.9	19.6	-18.0
	12%	1.4	20.7	-17.3
	18%	3.8	34.9	-23.4
Eye-In	6%	-4.3	14.5	-19.2
	12%	-2.0	27.7	-22.4
	18%	2.3	24.1	-17.4
Eye-Out	6%	3.3	40.9	-22.1
	12%	-3.2	20.2	-19.2
	18%	-1.4	32.4	-20.8

Finish

Location	Mass	Bend Position (deg)	Flex/Ext Position (deg)	Rotate Position (deg)
Elbow-In	6%	-0.1	8.0	3.2
	12%	2.4	9.9	-3.5
	18%	-2.6	-1.5	-0.8
Elbow-Out	6%	-1.5	4.7	-5.6
	12%	-1.1	12.0	2.0
	18%	2.1	15.7	-6.7
Eye-In	6%	-3.1	-1.6	-1.5
	12%	0.2	8.1	-7.3
	18%	-1.0	14.1	2.0
Eye-Out	6%	1.3	20.1	-5.3
	12%	-2.2	-1.1	3.1
	18%	-0.4	13.0	-6.0

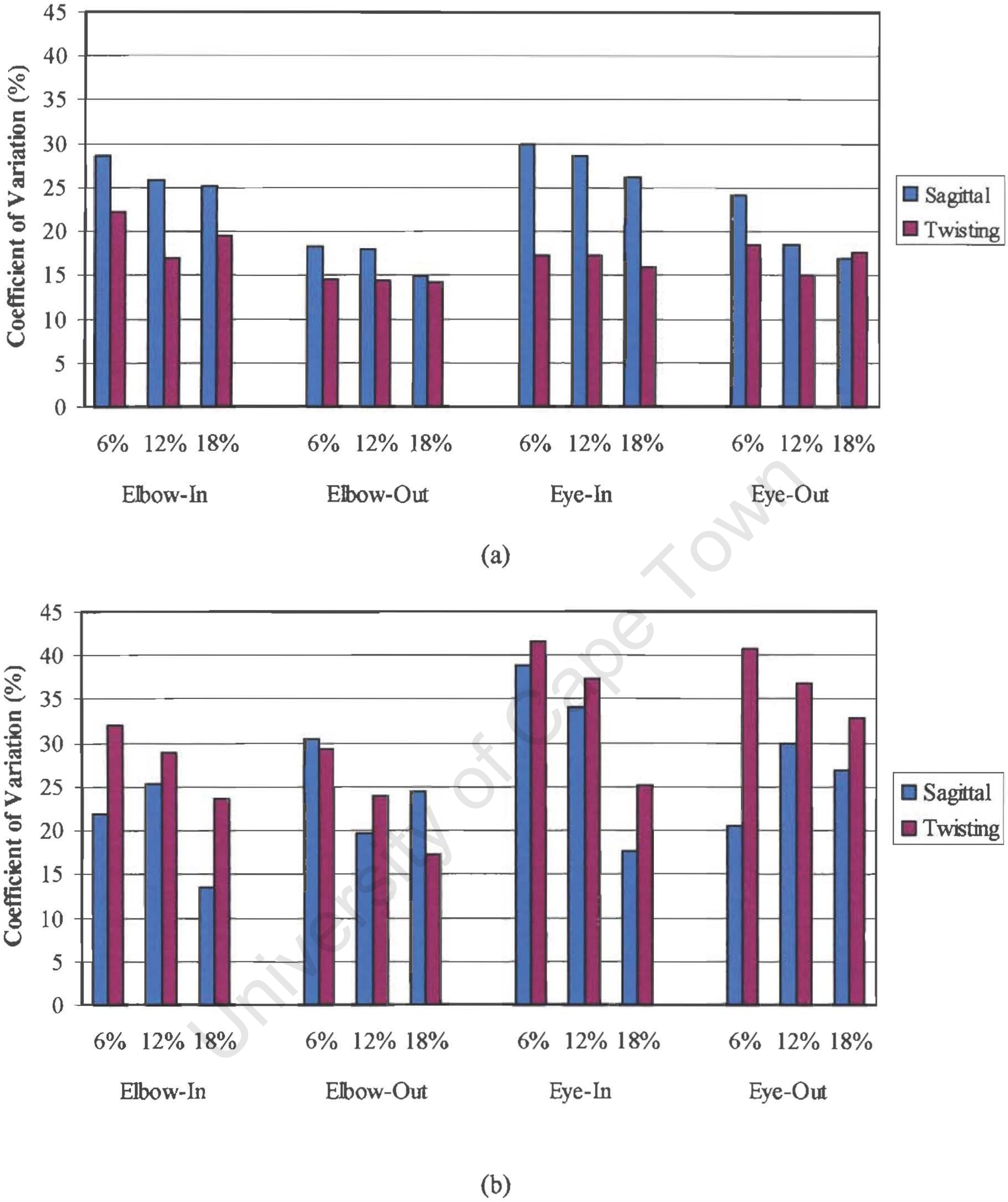


Figure 6.3: Mean variability in the start (a) and finish (b) of thoracolumbar positions in the sagittal and twisting planes.

Table 6.3: Mean maximum kinematic values in all three planes.

		Bend Right			Flexion			Rotate Right		
Location	Mass	Position (deg)	Velocity (deg.s^{-1})	Acceleration (deg.s^{-2})	Position (deg)	Velocity (deg.s^{-1})	Acceleration (deg.s^{-2})	Position (deg)	Velocity (deg.s^{-1})	Acceleration (deg.s^{-2})
Elbow-In	6%	2.9	6.8	42.5	18.1	14.8	110.4	5.7	49.4	158.5
	12%	3.6	10.2	53.4	25.0	24.4	141.5	4.1	54.8	184.8
	18%	5.0	11.9	61.9	33.0	40.9	231.6	4.5	70.4	263.0
Elbow-Out	6%	4.8	8.3	47.1	31.5	25.8	175.0	-2.6	50.6	173.9
	12%	5.6	8.7	50.4	43.9	39.7	238.6	-5.1	59.6	210.2
	18%	5.4	9.8	56.7	54.3	60.7	369.8	-3.6	73.2	266.2
Eye-In	6%	-1.7	12.3	52.4	13.5	18.3	130.0	0.2	42.3	139.3
	12%	-1.3	11.7	54.5	21.5	35.4	215.8	-0.4	50.4	173.4
	18%	0.3	15.0	69.3	33.6	64.4	372.6	4.4	76.4	275.5
Eye-Out	6%	-0.1	12.4	54.3	25.7	31.6	183.7	-4.7	44.2	167.7
	12%	1.9	12.6	59.8	38.9	50.0	303.9	-5.9	53.7	196.3
	18%	2.1	12.7	61.5	48.2	71.2	420.5	-3.6	73.1	283.1

		Bend Left			Extension			Rotate Left		
Location	Mass	Position (deg)	Velocity (deg.s^{-1})	Acceleration (deg.s^{-2})	Position (deg)	Velocity (deg.s^{-1})	Acceleration (deg.s^{-2})	Position (deg)	Velocity (deg.s^{-1})	Acceleration (deg.s^{-2})
Elbow-In	6%	-1.1	-10.4	-46.2	5.7	-32.5	-129.3	-17.3	-15.5	-125.9
	12%	-2.1	-14.3	-64.4	8.9	-45.1	-198.8	-20.8	-18.3	-119.9
	18%	-1.9	-19.8	-80.5	9.0	-75.3	-338.1	-23.8	-28.4	-139.4
Elbow-Out	6%	1.0	-9.4	-47.1	7.9	-69.4	-258.0	-22.7	-19.1	-115.3
	12%	0.8	-12.0	-56.4	12.4	-100.0	-377.1	-28.9	-24.6	-114.8
	18%	-0.2	-14.5	-64.7	13.9	-128.9	-506.1	-29.6	-32.4	-145.6
Eye-In	6%	-6.4	-6.6	-46.3	-3.3	-47.0	-169.8	-18.2	-13.5	-87.5
	12%	-5.8	-8.8	-56.1	-4.0	-76.9	-298.4	-22.5	-17.8	-95.8
	18%	-5.0	-13.0	-73.6	-5.3	-130.7	-539.0	-24.5	-27.7	-163.8
Eye-Out	6%	-5.0	-7.3	-47.9	2.3	-73.8	-271.6	-22.0	-19.0	-93.5
	12%	-3.4	-9.2	-54.8	4.0	-109.8	-432.5	-27.5	-23.4	-113.7
	18%	-3.3	-12.0	-62.6	5.4	-141.2	-572.9	-27.7	-29.8	-155.0

Table 6.4: Summary of statistical analyses of selected LMM values.

	Variable	Load	Location
Start Position	Bending		**
	Flexion/Extension	**	**
	Rotation	*	**
Finish Position	Bending		**
	Flexion/Extension	*	**
	Rotation		**
Lateral Plane	Right Bending Displacement		**
	Right Bending Velocity		
	Left Bending Displacement		**
	Left Bending Velocity	*	
	Maximum Acceleration		
	Maximum Deceleration	**	
Sagittal Plane	Flexion Displacement	**	**
	Flexion Velocity	**	
	Extension Displacement		**
	Extension Velocity	**	*
	Maximum Acceleration	**	
	Maximum Deceleration	**	**
Twisting Plane	Right Rotation Displacement		**
	Right Rotation Velocity	**	
	Left Rotation Displacement	**	**
	Left Rotation Velocity	*	
	Maximum Acceleration	**	
	Maximum Deceleration	**	

Note: * - Statistical difference at $\alpha < .05$
** - Statistical difference at $\alpha < .001$

Table 6.5: Results from the statistical analyses of the effects of load mass and pull location on the time of occurrence of peak values for selected lumbar motion monitor variable.

Kinematic Variable	Mass Effect	Location Effect
Sagittal Extension Velocity	0.01	<0.001
Sagittal Extension Acceleration	0.003	<0.001
Rotational (Right) Velocity	0.01	0.003
Rotational (Right) Acceleration	<0.001	<0.001

6.4 Discussion

Introduction

While there is a plethora of data describing the capacity of subjects to exert maximal pull forces in the horizontal direction, there is limited information regarding how these tasks are executed under submaximal repetitive conditions or when the operator is required to adopt awkward working postures. Haslegrave *et al.* (1997) found that the effects of task factors such as reach distance and direction of force exertion are highly complex and have significant underlying influences on the manner in which a task is executed. Marras *et al.* (1993) have advocated the importance of measuring the dynamic characteristics of a MMH activity in the context of real occupational activities in order to better understand how observed spinal kinematics might be related to the attributable risk of injury to an operator. While they have presented data related to occupations involving lifting activities, there currently does not appear to be an available data set of occupationally-specific kinematics of pulling activities.

This methodology includes four different pull origins which are related to subject relative anthropometric measures. These pull location origins were selected for two reasons. Firstly, this methodological approach has not been well explored in the literature, yet pull exertions occurring towards the extremes of the reach envelope are most likely responsible for reduced mechanical efficiency and higher potential for operator injury. More experimental documentation about the types of postures operators assume in industrial settings is needed and would be of benefit in the design of future experiment methodologies. Secondly, MacKinnon (1998) reported that as the pull exertions increased in distance from the floor and the sagittal plane midline of the operator, maximal isometric pull strength decreased. While maximal strength exertions were not explored in this study, it would be of interest to examine changes in operator performance as pull origins were relocated away from the centre of mass of the operator.

A decision was made at the onset of the study not to control for the speed of movement. This was considered in order to explore whether changes in pull location and load might have an effect upon the load or LMM kinematics. Often movement speed is fixed due to production controls, but whether these speeds reflect operator-chosen performance speeds is not generally considered. As indicated in the results section, there was no significant effect due to pull load or location on the load velocity. This is certainly interesting from a motor control perspective and further research into the reasons for this consistency is required. This lack of statistical difference in load velocity also allows for a more straightforward comparison of LMM data between experimental conditions. As will be discussed later in this section, there were differences in the movement speeds of the thoracolumbar segment across conditions in spite of the consistent movement speeds of the load. A better understanding of how the trunk segment motion is affected by load or handle position might reveal why load kinematics remained so consistent.

Data provided by an exoskeleton device estimating thoracolumbar spine motion does not provide appropriate information to warrant an extensive analysis of the association between trunk kinematics and risk of low back pain or overexertion. In the absence of available information on spine kinematics of pulling motions collected *in situ*, these data do provide valuable information about trunk motion under various forms of pulling exertions. The following discussion will report on the ranges of motions of the thoracolumbar spine, the variability of some of theses measures and the variability in timing of maximum kinematic measures during the movement cycle. Finally, these LMM measures will be compared to similar metrics recorded for lifting activities performed *in situ* (Marras et al., 1993; 1995) for which risk of occupational injuries are statistically related.

Load magnitudes and kinematics

Some ergonomic field studies have measured cart-type pulling forces (Frings-Dresen *et al.*, 1995; van der Beek and Frings-Dresen, 1995), but few have reported on stationary pulling activities. Frings-Dresen *et al.* (2000) measured single handed pull forces for twelve tasks considered to be typical of the construction industry. The mean forces ranged from 48.9 to 191.9 N and the peak forces ranged from 77.4 to 589.0 N. While these loads are reasonably comparable to those observed in this study (range of 35 to 153 N), these authors did not describe the postures their subjects assumed when exerting these forces. Hoozemans *et al.* (2001) reported on measures of forces for single-handed pull exertions on a concrete hopper. They reported maximum force values in excess of 245 N. These are higher than those employed in the present study. Paquet *et al.* (1999) observed that steel workers and carpenters exerted push and pull forces (note that these authors did not distinguish between pushing and pulling activities) for loads of no more than 225 N approximately 2-4 % of the time spent during concrete masonry operations. Although these authors did consider trunk postures in their exposure assessments, it was difficult to determine from these data, as reported, what postures were common to push or pull exertions. While task demands and operator postures are different in those studies that reported pull force values, it seems that the experimental loads employed in the current study may be considered characteristic of those found *in situ*.

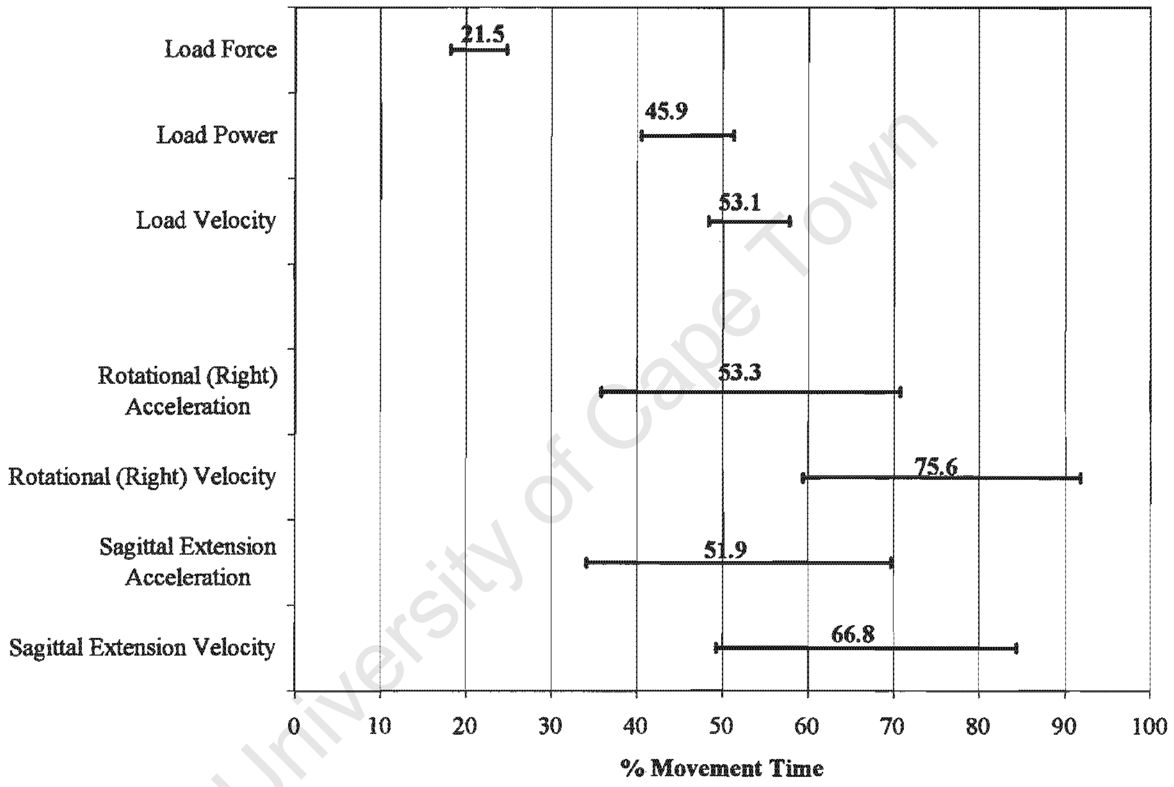


Figure 6.4: Variability, expressed as one standard deviation above and below the mean, of the time at which the maximum kinematic value occurred in the pull exertion (expressed as a percentage of movement time). The numbers within the figure indicate the mean values.

It is interesting that guidelines recommended by Mital *et al.* (1997) suggest no frequent isometric horizontal pull forces exceed 100 N for men and 70 N for women, yet peak forces measured *in situ* are generally found to be greater. In comparison to the maximal isometric data presented by MacKinnon (1998), data reported for similar pull origins (estimations had to be made because the isometric data were reported in absolute distances from the floor and the sagittal plane of the operator) ranged from 172 to 241N at the elbow heights and 132 to 162N at the eye heights. If one considers the 18% lean body mass load used in this study, then this would represent group average exertions of 52.7 to 73.8% of MVC and 78.4 to 96.2% of MVC at elbow and eye heights respectively. Although no measures such as level of perceived exertion were recorded in this study, qualitative assessment would suggest that the subjects were not functioning at such high levels of exertion. This comparison creates questions regarding the validity of employing guidelines derived under isometric conditions for evaluation of more dynamic tasks.

Lumbar motion monitor kinematics during a single handed pulling exertion

It should be noted that inferences made from these data about spine mechanics are limited due to the fact that direct measures of the spine were not obtained. However, there is sufficient evidence to suggest that LMM measurements have a high degree of criterion-related validity (Marras *et al.*, 1992) and have been shown to produce repeatable results (Gill and Callaghan, 1996).

Data from this research provides evidence that spine kinematics (and presumably kinetics) are affected by both the load magnitude and the location of the origin of the pull vector about the frontal plane, even though the measures describing load kinematics remained relatively consistent throughout the experimental protocol. MacKinnon and Li (1998) described a similar outcome for lifting exertions, concluding that subject kinematics were a better discriminant between experimental conditions than measuring load characteristics.

Lateral plane kinematics

As illustrated in Figure 6.1, and supported by the statistical analyses (Table 6.4), subjects will bend slightly to the right when preparing for an exertion at elbow height and bend slightly to the left when initiating an exertion at eye height, although the total variation in position in this plane was +/- 6 degrees in each direction for all conditions (see Table 6.2). Maximal bending displacements, velocities and accelerations (see Table 6.3) exhibited no practical change with load or pull location. Increases in load did increase the velocity and acceleration values for bending motions to the left side, although these changes were small (ranges of 6.6 to 19.8 deg.s^{-1} and -46.2 to -80.5 deg.s^{-2}). There was a significant effect upon the final side bending position due to pull location (see Table 6.2). As part of the experimental protocol, subjects were instructed to pull on the load handle along a line perpendicular to the frontal plane. Although the subjects assumed different postures at the origin of the pull location, it appears that subsequent spine kinematics remained relatively similar in this plane during the exertions at each pull location. In terms of workstation design, if the direction of the pull vector were free to vary, regardless of it origin, the lumbar side bending kinematics would likely be different to those recorded in this experiment.

Sagittal plane kinematics

Both load magnitude and pull location had a significant effect upon the spine kinematics in the sagittal plane. Subjects increased the amount of back flexion at the start of the pull cycle as load increased (see Table 6.2). Generally there was more back flexion for the pulls at elbow height compared to eye height. This probably occurred because the simplest strategy to move the hand to an eye height pull location would be to straighten the back, as well as flexing the arm at the gleno-humeral joint. The tendency to increase back flexion suggests that the subject anticipated the demands of the higher loads and awkward positions and was positioning the trunk to generate greater momentum in order to execute the task. Adopting non-neutral trunk postures during MMH activities has been shown to have a strong and consistent relationship between musculoskeletal disorders of the back in a cohort of workers in the automobile manufacturing industry (Punnett *et al.*, 1991).

As expected, subsequent back extension velocities and accelerations during the pull exertions were found to increase significantly with load (see Table 6.3). Back extension kinematics also increased significantly as a function of pull location. More lateral pull locations were associated with higher back extension velocities and accelerations at both elbow and eye height, while exertions at eye height tended to have larger values than elbow height within each sagittal plane of pull.

Marras *et al.* (1993, 1995) employed a multiple logistics regression model to examine occupationally-related dynamic three-dimensional trunk motions during lifting. In their results, they suggested that high back extension velocities were associated with occupations and tasks that were at high risk for developing low back disorders. Increased back extension velocities and accelerations will likely indicate higher muscle forces in the erector spinae muscles resulting in larger compression forces acting on the spine (Marras and Wongsam, 1986). Larger velocities and accelerations in this plane might also reflect a pulling strategy that exploits the large inertial properties of the trunk segment.

The findings from this study demonstrate different trends to those of Davis and Marras (2000) who reported that as load masses increased for a lifting activity, the trunk velocities in the sagittal plane decreased. The authors suggested this was a protective strategy to reduce spinal loading with increasing loads. This was not the case for the pulling exertions monitored in this study. Often the larger muscle groups of the lower limbs are employed to lift an object, particularly when proper lifting mechanics are encouraged. However, the capacity of the smaller, more gracile muscles of the upper body are likely maximised at relatively small pulling loads. Heavier pull loads would require increasing force contributions by the back musculature to compensate for the relatively weaker upper limbs, particularly when awkward postures are required of the operator.

Twisting plane kinematics

There was a statistically significant trend for subjects to initiate the pull exertion with the trunk twisted towards the left (see Table 6.2). Pope *et al.* (1987) recognized this pre-rotation as a strategy to improve axial torque production in the opposite direction. This axial rotation generally increased as load increased. While there was a significant difference in starting axial rotation position due to pull location, *post hoc* analyses indicated that these differences were between the medial and lateral sagittal plane pulls and not a function of pull height. Axial trunk rotation is often necessary during MMH activities in order to position the upper arm in a mechanically advantageous position (Amell *et al.*, 2000). While a statistically significant difference was reported for the final axial rotation position (see Table 6.2), this difference probably has no biomechanical significance as the range of final positions was from 7.3 degrees of left rotation to 3.2 degrees of rotation to the right when considering all experimental variants. There was an increase in the magnitudes of rotational velocities, accelerations and decelerations for each pull location with an increase in load (see Tables 6.3 and 6.4). This was likely due to the increased moments of inertia about the longitudinal axis with increased loads. However, there were no significant differences between the pull locations within a load condition. It was initially expected that the more lateral pull locations would require increased axial rotational accelerations to complete the task given the expected increased moment of inertia of the head-arms-trunk segment about the longitudinal axis. It has also been reported that there is a reduction in force producing capacity of the operator in more lateral pull locations under isometric conditions (MacKinnon, 1998). It seems that in this plane of trunk motion, it is not changes in spine rotation strategies that produce the required additional forces across pull locations compared to those needed for the inside elbow height. Most likely it is the muscles controlling shoulder motion that moderate these increases in force.

Figure 6.3 illustrates the variability across subjects in the start and finish position for the sagittal and twisting plane kinematics. It should be noted that these coefficients of variation (CV) values may seem large. However, these absolute position magnitudes, both in the start and finish orientations (refer to Table 6.2), were small, thus even small standard deviation values will result in high CV scores. It is the trends in these CV scores due to load and handle positions which are most interesting.

The CV values are smaller at the start of the pull than at the end of the pull. This reflects the levels of experimental control associated with the starting hand and feet positions. There was smaller and more consistent variability in the amounts of axial rotation at the start of the movement across loads and pull locations. There was considerably more variability in the initial positions in the sagittal plane. This likely represents the trade-off between the shoulder and trunk postures available to reach for the load handle at the start. Most interesting is that the variability became significantly smaller ($p = 0.038$) with increasing load. This reflects the greater importance of trunk posture in the sagittal plane as load increases.

The variability in the finish positions was considerably greater than in the start positions, particularly for the amounts of axial rotation. This reflects the considerable degree of freedom an operator has in order to exert a single-handed pull force even for a specified vector. The increase in variability was most noticeable for the axial rotation positions. While these decreased with increasing load ($p = 0.026$), the variability was greater for the Eye-In and Eye-Out positions. The magnitudes in variability in the finish position for the sagittal plane kinematics were similar to those for the start, although the trends associated with pull load disappeared. It seems that the subject chooses to vary trunk rotation to a greater extent than back extension when comparing the start to finish positions for various pull loads and initial handle locations.

Kinematic timing effects

There were no significant differences in the movement time across the 12 experimental conditions, and thus normalizing these data in time should not result in significant temporal distortion between experimental conditions. Load kinematics displayed very little variability in the time at which peak velocity, force and power occurred within the pull exertion. These results demonstrate that maximum power exerted on the load generally occurs near mid-cycle of the exertion, with load velocity reaching a maximum shortly thereafter. This relationship between muscle force, velocity and power has been described in the past (Hill, 1938) and seems to remain consistent with load kinematics created by whole-body exertions. Dempsey (2002) suggested that mechanical power is an important consideration in evaluating lifting capacity. Similarly, generation of maximum power within a movement activity might be considered an important event to compare other kinematic and kinetic measures of a manual materials activity such as pulling.

Table 6.5 and Figure 6.4 reveal the differences in the time at which the peak value for pertinent load and lumbar motion monitor kinematic measures occurred within the movement cycle. All lumbar motion monitor measures were affected by the pull load and location variables. In fact, all four measures were affected in the same manner across experimental conditions. With respect to the pull load effects, as load magnitude increased the relative time at which the peak value occurred in the movement cycle increased. Pull location also had a consistent effect on these values. In all cases, the Eye- and Elbow-In times to peak measures occurred before the Eye- and Elbow-Out times to peak measures.

There appears to be a temporal coordination in the thoracolumbar motion about the sagittal and horizontal planes. Peak thoracolumbar extension and rotational velocities occurred near similar times in the pull cycle. These peak velocities occurred relatively late in the movement cycle, well after the peak load velocity (see Figure 6.4). This timing differential would be desirable as it likely that the trunk velocities had smaller magnitudes when the largest forces were being exerted upon the load by the hand. Furthermore, under these circumstances the musculo-skeletal system would be at a lesser risk for over-exertion injury. As expected, the peak acceleration values for both velocity measures preceded peak velocities.

Thoracolumbar kinematics and risk of injury

Marras *et al.* (1993, 1995) reported the LMM kinematic characteristics for 400 industrial jobs that included repetitive lifting tasks collected in 48 different industries. Employing medical and injury records, they classified these jobs as high or low risk for developing low back disorder and then statistically associated these jobs to the measured spinal kinematics. Table 6.6 reproduces selected workplace and lumbar motion monitor factors associated with low, medium and high risk of occupational injury that Marras *et al.* reported. While these data included both mean and standard deviation values, the data do not appear to be normally distributed if one considers the magnitude of the variance measures. They found trunk velocity in all three planes to be the strongest predictors of risk and, in particular, sagittal velocity produced the greatest odds risk ratio.

While the data from Marras *et al.* (1993, 1995) seem to represent spine kinematics from mixed occupational activities that feature lifting tasks, the ranges of trunk motion in all three planes for the pulling actions examined in this study are comparable (refer to Table 6.3). Given the kinesiological similarities between these studies, it was considered acceptable to compare the spinal velocity and acceleration profiles between these data sets.

In comparison to the maximum bending velocity values reported by Marras *et al.* (1993, 1995), values from this study were consistently in the low risk category across all loads and pull locations. However, sagittal and rotational values for the pulling activities were generally larger than those reported for high risk lifting jobs. Of the 12 pull conditions examined in this study, 11 were within one standard deviation of the mean maximum extension velocity value for high-risk jobs, while 3 conditions exceeded the mean value. More interestingly, all pull conditions examined in this study were within one standard deviation of the mean maximum rotational value reported for high-risk jobs and of these 10 conditions exceeded the reported mean value.

While LMM data for high-risk tasks from Marras *et al.* (1993, 1995) were reported for lifting activities with a mean load of 84.7N, the magnitude of absolute masses studied in the current experiment ranged from 39.2 to 147.2N with an average exertion against a 56.5N load. While the direction of the load force vector would be different for a mass being lifted compared to a mass being pulled, the magnitude of forces acting on the hand(s) between these two activities can be considered comparable. Although changes in axial rotation of the spine did not seem to play an important role in mediating changes in demands with pull locations across loads, these values did regularly exceed those considered to place an operator at a high attributable risk for low back disorders due to lifting activities (Marras *et al.* 1993, 1995).

Table 6.6: Selected workplace and lumbar motion monitor data reproduced from Marras *et al.* (1995)

Factor	**Unit**	**Low** *mean*	**Risk** *SD*	**Medium** *mean*	**Risk** *SD*	**High** *mean*	**Risk** *SD*
Workplace Factors							
Max. Mass Handled	N	29.30??	48.87	75.00	76.88	88.40	75.43
Ave. Mass Handled	N	37.15	60.83	98.23	101.78	113.69	87.23
Sagittal Plane							
Max. Flexion Position	deg	10.37	16.02	17.61	16.17	20.03	18.16
Max. Velocity	deg/s	38.69	26.52	53.69	36.37	59.00	36.19
Max. Acceleration	deg /s^2	226.04	173.88	306.74	211.84	340.27	211.65
Twisting Plane							
Max. Flexion Position	deg	-1.92	5.36	-0.01	6.17	2.09	8.65
Max. Velocity	deg/s	38.04	17.51	48.48	27.03	49.72	27.64
Max. Acceleration	deg /s^2	269.49	146.65	341.72	233.75	320.91	191.74

Norman *et al.* (1998) reported that full-time, hourly-paid automotive workers who reported at least one complaint of low back pain in the 90 days preceding the study handled significantly higher loads and demonstrated greater trunk velocities compared to those who made no claims of low back pain during the same period. Similar to Marras *et al.* (1993, 1995), these data represented summaries of the various tasks related to this industry and were not specific to pulling exertions. Compared to the present study, those subjects who reported low back pain demonstrated smaller trunk velocities (41.5 +/- 15.14 deg.s^{-1}), but were handling heavier loads (222 +/- 201 N). Employing results from an odds ratio analysis, these authors also concluded the trunk kinematics and external load variables were independent factors in the prediction of low back pain.

While these data collected in this study correspond to kinematic profiles from a controlled, experimental protocol on pulling tasks, it is clear that these trunk motions are consistent with those observed within a variety of occupations. Furthermore, these occupations and associated trunk motions have been shown, from a statistical perspective, to be related to the onset of low back pain. Therefore, it is recommended that occupations that require pulling tasks to be performed under similar load and postural constraints be closely scrutinsed, as these exertions are likely to be associated with the occurrence of low back pain.

6.5 Conclusions

This paper examines the lumbar spine kinematics for a variety of pull exertion postures for three different loads. With respect to the study hypothesis, as the pull location moved away from the sagittal and frontal planes and as pull load increased the magnitudes of thoracolumbar motion increased. The LMM kinematics describing submaximal pull force exertions measured about various locations in the frontal plane are comparable to values obtained for those of occupationally-related lifting activities considered to place the operator at higher risk for developing low back disorders. Therefore, workstations that predispose the operator to awkward pulling postures or heavy pull loads should be re-designed as the inherent risk for low back pain in these types of activities could also considered to be high.

While back extension strategies seem to mediate the changes in exertion requirements for increasing loads or changes in pull force origin, this finding doesn't seem to be consistent with changes in axial rotation kinematics. If the assumption that the moment of inertia of the head-arms-trunk segment increases as the pull force origin moves laterally from the longitudinal axis is true, and increases in back velocities and accelerations about this axis are not observed, then it stands to reason that either forces generated from the foot-and-floor interface or by the upper extremity musculature accommodate the changes in force demands. Future studies should probably include the measurement of shoulder kinematics as well as ground reaction forces at the foot-floor interface.

Whether the loads imposed upon the spine during these pull conditions exceed biomechanical tolerances is unknown. However, trends indicate that as load increases and pull locations occur closer to the extremes of the reach envelope, the stresses exerted on the spine, and most likely on the shoulder joint as well, will increase. It is concluded that repetitive, submaximal pull exertions such as those examined in this study may predispose an operator to risk of overuse injuries, and such handle orientations should be avoided in workstation design particularly if coupled with heavy pull loads.

Chapter 7

Effects of Posture on the Recruitment Magnitudes of Selected Trunk and Shoulder Muscles During Pull Exertions

The purpose of this paper was to examine the effects of pull exertions about various locations of the frontal plane on electromyographic (EMG) recruitment levels for eight muscles (left and right erector spinae, left and right external obliques, right trapezius, latissimus dorsi, deltoid and biceps brachii). Twenty male volunteer subjects exerted one-handed pulls against three loads (6, 12, 18% lean body mass) at four pull locations. Results indicate that neither load magnitude nor pull location had a significant effect on pull time when the length of displacement was standardised. EMG activity for all muscles increased with increases in load in a scaled fashion, although only six of the eight muscles demonstrated an effect due to pull location. In general, more lateral and superior pull origin locations elicited higher levels of EMG activity. The latissimus dorsi and deltoid did not demonstrate a pull location effect but were found to be highly active throughout all experimental conditions. Evidence from this study reveals that musculature causing both trunk and shoulder motion are highly involved in creating pull exertions about various locations in frontal plane.

7.1 Introduction

Various studies have reported that between 9 and 20% of all accident or overexertion injuries can be attributed to pulling or pushing activities (NIOSH, 1981; Statistics Canada, 1991; van der Beek *et al.*, 1999). These statistics should not be surprising, and may even be underreported (Kumar, 1994), in light of the work by Baril-Gingras and Lortie (1995) who found that nearly half of all manual materials handling activities performed in a warehouse setting were either pushing or pulling in nature. Interpretation of these data is further complicated by the fact that pulling and pushing activities are generally not categorized separately when accidents or injuries are reported. Unlike lifting and lowering activities, where similar muscle groups are employed under different neuromuscular strategies, pulling and pushing activities demonstrate different kinetic profiles (Hoozemans *et al.*, 1998).

Giroux and Lamontagne (1992) reported that the incidence of occupational cervicobrachial disorders (OCD) has increased steadily among industrial workers since the early 1960's even though much progress has been made in providing ergonomically sound workplaces. These authors right hand and right lower limb dominance, an active lifestyle and participation in some form of regular weight training programme.

After the experimental protocol was explained and the subject was offered an opportunity to ask questions, informed consent was obtained as per ethical standards established by the University. Each subject was given an opportunity to attempt pull motions under approximated experimental conditions. The anthropometric measurements recorded for each subject are listed in Table 7.1. Detailed description of the anthropometric measurement procedures can be found in Pheasant (1988). Body density and percentage body fat were estimated using the procedures described by Jackson and Pollock (1978) and Siri (1956). Subjects were requested to return the following day to participate in the formal data collection session.

Table 7.1: Summary anthropometrics for twenty subjects.

Variable	**Mean**	**SD**	**CV**	**Min**	**Max**
Age (Yrs)	22.0	2.0	9.2	19.0	26.0
Mass (kg)	83.3	12.4	14.9	65.4	114.6
Body Fat (%)	12.9	5.5	42.6	5.9	24.2
Lean Body Mass (kg)	72.0	7.6	10.5	60.1	86.9
Stature (mm)	1853.7	42.5	2.3	178.9	194.8
Elbow Height (mm)	1157.5	28.4	2.5	110.1	124.3
Eye Height (mm)	1735.8	46.8	2.7	167.3	182.5
Humerus Length (mm)	380.2	16.4	4.3	35.0	41.2
Shoulder Width (mm)	482.8	42.6	8.8	35.2	54.8
Hip Width (mm)	355.8	19.0	5.3	31.9	41.2

Independent variables

Load conditions

Each subject was required to execute various pulling action against loads of 6, 12 and 18% of lean body mass. These loads were selected based on findings by MacKinnon (1999) and from pilot work done prior to commencement of the study. While values of 6, 12 and 18% lean body mass may seem unconventional, it was established that these values were sufficient to maximise the variance of the independent variable of load. Furthermore, pilot studies indicated that larger relative loads might have been too arduous and not typical of workloads found *in situ*.

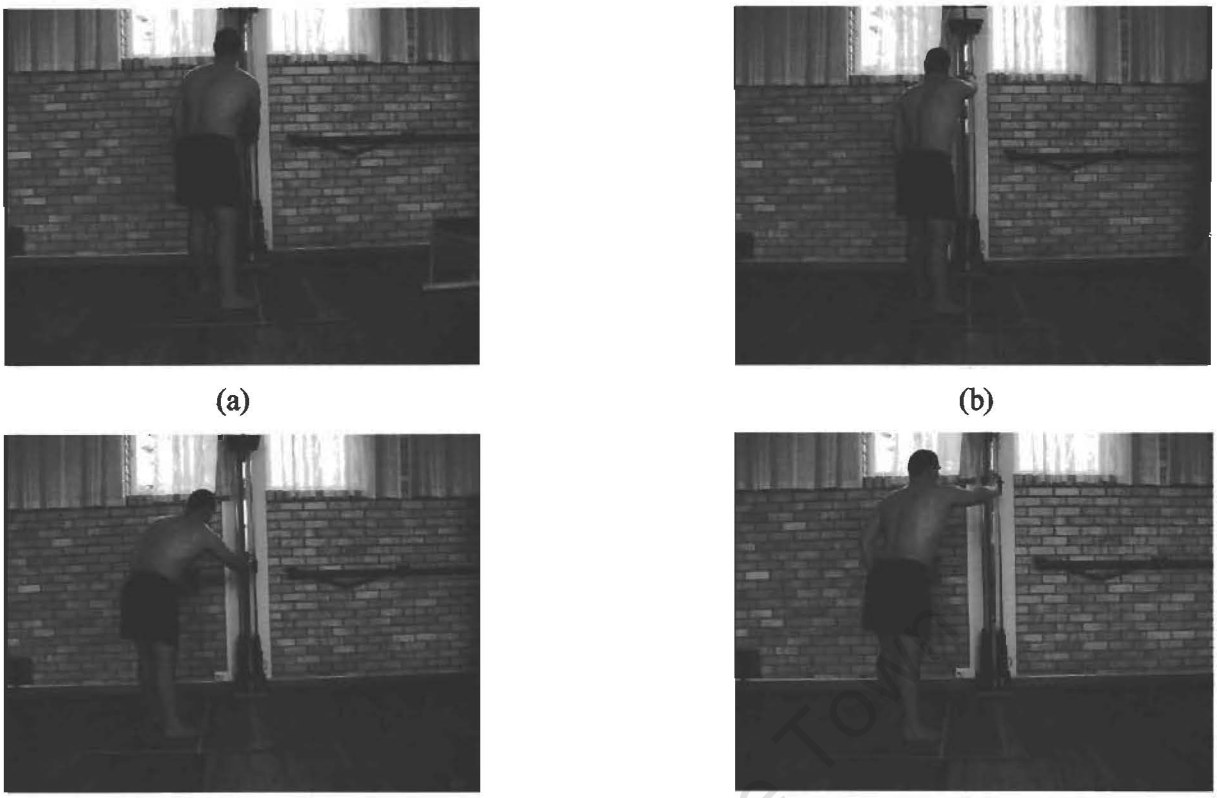
Location of pull origin

Pull exertions originating from four locations in the frontal plane were examined. These origins were expressed relative to the morphology of the subject within a standard planar coordinate system. Two pull heights were tested, orbital height and elbow height, through two parasagittal planes, one defined by the location of the gleno-humeral joint centre when the arm is held relaxed at the subject's side and the other at a lateral, horizontal distance defined by the distance of the centre of the subject's gleno-humeral joint to the centre of the elbow joint away from the previously described plane. Subjects were instructed to exert a pull in a horizontal plane relative to the pull height origin and within the sagittal plane defining the lateral location within the frontal plane. Figure 7.1 (a,b,c,d) illustrates these locations. Included in the figure caption are the reference names (*i.e.* Elbow-In, Elbow-Out, Eye-In, Eye-Out) employed in the remainder of the paper to describe each pull location.

Controlled variables

Only right-handed pull exertions were examined in this study. The subject was requested to maintain a grip on the handle attached to the load in a vertical orientation throughout the duration of each trial.

Foot placement was prescribed for each subject and kept constant for each experimental condition. Foot positions where asymmetrical, with the left foot in front of the right foot. The great toe of the left foot was a distance of 20% body stature from the frontal plane containing the origin of the pull. The two great toes were separated by a distance of 10% subject stature in the medial-lateral direction and by a distance of 25% stature in the anterior-posterior direction. The exact geometric specifications and rationale for these foot positions have been described elsewhere (MacKinnon, 2002). These positions were demarcated on a slip resistant surface prior to the arrival of the subject for the data collection session.



(a) (b)

(c) (d)

Figure 7.1: Location of Pull Origins: (a) Elbow height/sagittal plane dissecting gleno-humeral joint (Elbow-In); (b) Eye height/sagittal plane dissecting gleno-humeral joint (Eye-In); (c) Elbow height/sagittal plane located laterally (Elbow-Out); and (d) Eye height/sagittal plane located laterally (Eye-In).

Load displacement was also based on recommendations by MacKinnon (2002). A visual cue was clearly positioned at a distance of 20% of the subject's stature from the top most weight plate on the En-tree system (Enraf Nonius B.V., Holland). Subjects were requested to pull the load as close as possible to the demarcated height without hesitation or movement interruption to attempt targeting correction. In order to ensure the pull was executed in a horizontal plane, a freely hanging foam-padded target, with an auditory feedback mechanism, was appropriately positioned for each trial. Subjects were required to make contact with the foam pad with the dorsal aspect of the hand or the elbow at the end of each pull action. The foam target was lightweight and thought not to contain sufficient mass to influence the execution of the pull exertion.

Subjects were free to choose the tempo at which the pull actions were executed, although they were encouraged to maintain temporal consistency within a particular condition. No auditory or visual prompt was given to the subject in this respect. The subject was requested to provide a discernible pause in between each pull and load-return cycle but not to hesitate in the transition between the pull and load-return phases.

Dependent variables

Load kinematics

The En-tree isoinertial pulley system was employed to provide a horizontal resistance against which the subject exerted a pull and load-return action. The investigator could select loads in 0.5 kg increments. In order to expose the subject to the required 6, 12 and 18% lean body mass loads, necessary additional mass was secured to the top weight plate of the system. The height of the handle, attached to the load via a cable system, was adjustable to either the subject's elbow or eye heights. The En-tree device measured load displacement via a series of potentiometers at a sampling frequency of 100 Hz. Velocity-, force- and power-time profiles were derived by employing a finite differences algorithm contained in the software purchased with the device.

Muscular activity

The ME3000P (Mega Electronics Ltd, Kuopio, Finland) unit was employed to collect the electromyographic profiles. The external unit was connected to the communications port of a personal computer, via an optic cable, for online data collection. The EMG profiles from the following muscles in the trunk region were collected for each condition: left and right erector spinae (at the level of the fourth and fifth lumbar vertebra) and left and right external obliques. The following muscles in the shoulder region were collected on the right side of the body: trapezius, latissimus dorsi, deltoid and biceps brachii. Each channel was sampled at 1000 Hz, band-pass filtered between 20 Hz and 500 Hz, amplified (differential amplifier, common mode rejection ratio ≥ 130 dB, gain x 1000, noise ≤ 1 μV) and analogue-to-digitally converted (12-bit), and stored on personal computer for further analysis. The amplification of the biological signal was done at the grounding electrode site (which was located approximately 100mm from the recording site) in order to minimise signal artifacts caused by movements and external noise. Following the data collection period, several maximal isometric voluntary contractions (MVC) were elicited against manual resistance for each muscle and the EMG signals from these activations were also stored for further analyses. The MVC's were elicited at about mid range of motion of the joints over which these muscles pass. Each raw EMG signal was full-wave rectified and submitted to a linear envelope (4 Hz). Only the concentric pull phases (pull away from the origin) were considered in this investigation. The mean voltage for each muscle throughout each pull action was determined. This value was normalised by employing the mean voltage from the largest activity sampled from several consecutive MVCs exerted by the subject.

Experimental design and collection protocol

A randomised block factorial design was employed in this study. Two independent variables were defined: (1) pull load and (2) location of pull force about a subject –specific position relative to the frontal plane.

Prior to data collection, Ag/AgCl electrodes with a recording surface of 100 mm^2 were applied to the mid-belly of each muscle in a bipolar configuration in accordance with the manufacturer's suggested instructions. The distance between the centres of the recording surfaces of active electrodes was standardised to 15mm. Electrode placement included shaving the body hair from the recording sites and cleaning the skin with alcohol swabs. The electrodes and wires were secured to the subject using adhesive tape. No electrode manipulation occurred during the data collection period.

The subject was then asked to stand on the slip resistant surface that demarcated the standardised foot positions. The feet were aligned to the investigator's satisfaction. As in the session during which anthropometric data were collected, the subject was provided ample time to familiarise himself with the data collection protocol and attempt all conditions prior to actual data collection. Data collection did not commence until both subject and experimenter were satisfied that the subject could competently execute the task.

The subject was asked to exert approximately 10 pulls for each condition. Five consecutive efforts were selected for subsequent analysis. Five repeated measures have been reported to be sufficient to obtain an unbiased estimated of the demands imposed on the subject (van der Beek *et al.*, 1999). More pull efforts than needed for the analyses were collected in order to minimise the effects of data loss due to signal distortion or irregular execution of the task by the subject.

Data from the EMG unit and the En-tree isoinertial pulley system were synchronised upon commencement of data collection of each trial using a switch that interrupted data transmission through the communications port of the computer connected to each of the measurement devices. Subsequent pull actions were identified by employing the displacement profiles collected by the En-tree unit.

Each condition required approximately 30 – 60 seconds to complete. Subjects were given a minimum of 150 seconds of rest between each trial in order to minimise the effects of fatigue. Load and pull force locations were randomly presented to each subject in order to eliminate any order effects.

Statistical analyses

Each of the eight muscles were analysed in separate analyses as were the following kinematic variables derived from the En-tree system: load displacements, pull times, peak and mean pull velocities, peak and mean pull forces and peak and mean pull power. A two-factor analysis of variance for repeated measures was employed to assess the effect of load and pull location on the dependent variables. If a significant difference was detected for each of the main effects, the Scheffé *post hoc* method was employed using a 95% simultaneous confidence interval for specified linear combinations.

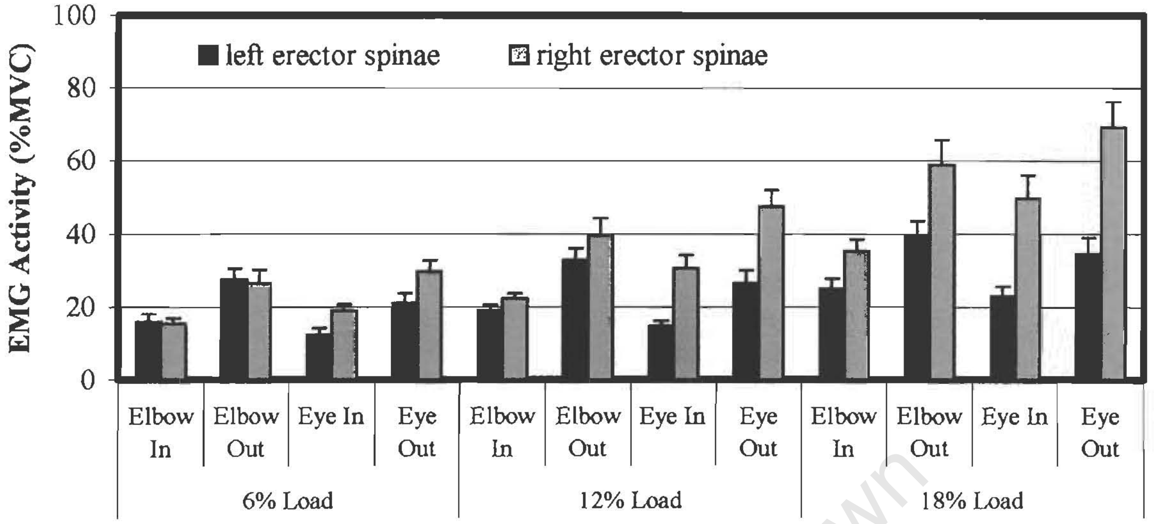
7.3 Results

Load kinematics

There were no significant differences in the load displacements, pull times and peak and mean pull velocities between load and pull locations within each load. As was to be expected, there were significant differences for peak and mean pull forces ($p < 0.0001$ and $p < 0.0001$ respectively) and peak and mean pull power ($p < 0.0001$ and $p < 0.0001$ respectively) between all load conditions but not between the four pull locations within a load condition.

Electromyographical data

Because the load kinematics displayed no displacement or temporal effects, the subsequent statistical analysis of the EMG data was performed on the %MVC data. The mean activity for each pull action for each muscle was expressed as a percentage of the mean maximal voluntary isometric activation (Figures 7.2 and 7.3). These data can be used to assess the relative intensity of each muscle for each load and location condition.



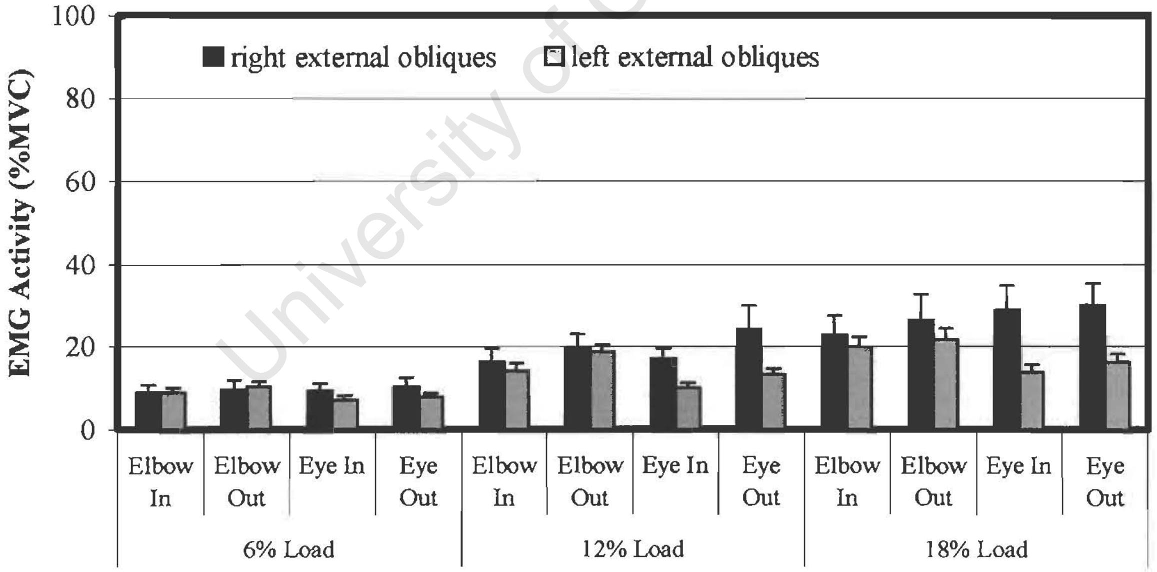
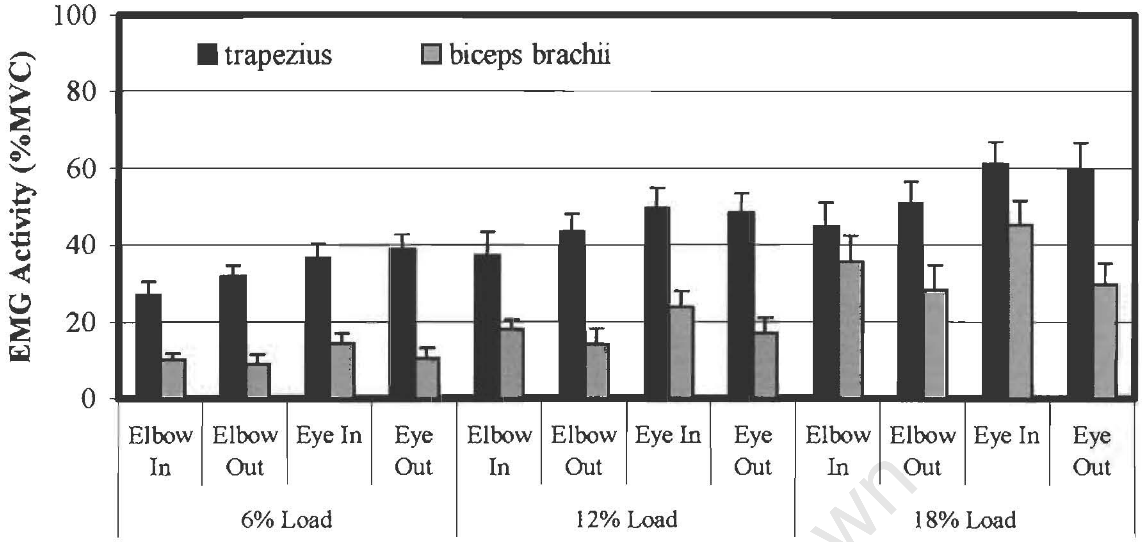


Figure 7.2: Mean (and standard error of the mean) EMG activities for each pull condition for four muscles acting on the trunk.



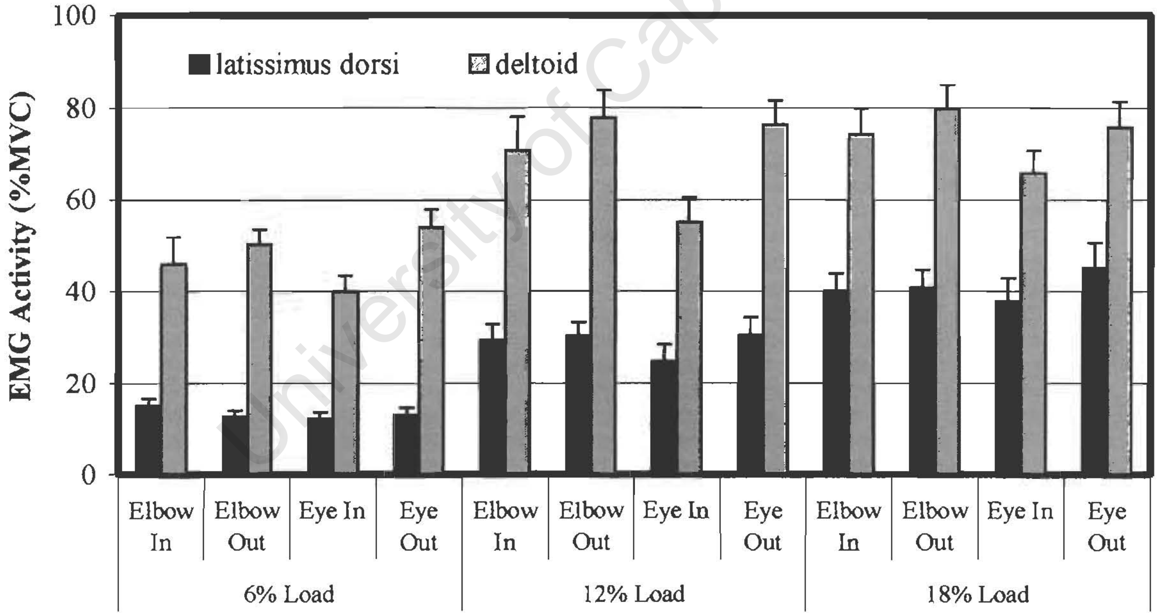


Figure 7.3: Mean (and standard error of the mean) EMG activities for each pull condition for four muscles acting on the shoulder joint.

Pull load effects on EMG magnitudes

Load had a significant effect on the level of recruitment for all eight muscles monitored in this study. For all muscles, as load increased so did the recruitment levels ($p< 0.0001$). This suggests that the eight superficial muscles selected for scrutiny were likely prime movers or stabilizers in the genre of pulling actions examined in this study.

Pull location effects on EMG magnitudes

In six of the eight muscles examined, an effect due to pull location was identified ($p< 0.001$). Only the latissimus dorsi and biceps brachii muscles did not alter the recruitment levels due to changes in pull location for each load condition. Table 7.2 contains information regarding the pair-wise *post hoc* analysis done for the remaining six muscles. It was decided to compare pull locations to the Elbow-In locations for each load, as this has been reported to be a near-optimal handle location for producing maximal, single-handed isometric pull exertions (MacKinnon, 1998). A positive (+) sign indicates a statistically significant increase from the Elbow-In position and a negative (-) sign indicates a statistically significant decrease in recruitment activity compared to the Elbow-In position. The changes with pull location were consistent across all three load conditions.

Table 7.2: Direction of statistically significant changes in muscle recruitment for each pull location with respect to the Elbow-In position.

	Left Erector Spinae	**Right Erector Spinae**	**Right External Oblique**	**Left External Oblique**	**Trapezius**	**Bicep**
Elbow In vs Elbow Out	+	+		+	+	
Elbow In vs Eye In		+	+	-	+	+
Elbow In vs Eye Out	+	+	+		+	

Peak Muscle Activity Sequencing

The time (expressed as a percentage of total movement time) at which the maximal EMG activation occurred was determined for each muscle for each condition. These data were examine for load and pull location effects employing a repeated measures ANOVA. Table 7.3 reports the level of statistical significance for each main effect.

Table 7.3: p-values associated with the mass and pull location effects on the time of peak activity for each muscle monitored.

Muscle	**Mass Effect**	**Pull Location Effect**
Left Erector Spinae	0.013	NS
Right Erector Spinae	NS	NS
Left External Obliques	NS	NS
Right External Obliques	NS	<0.001
Right Latissimus Dorsi	NS	NS
Right Trapezius	NS	NS
Right Deltoid	0.045	NS
Right Biceps	NS	0.002

Note: 'NS' indicates 'No Statistical Significance'

Figure 7.4 illustrates the variability (± 1 standard deviation from the mean) of the occurrence of peak activities for each muscle for all conditions related to movement duration. Those data highlighted with either red or blue lines indicate the muscles for which a statistical effect was detected, either due to change in mass or pull location (see Table 7.3).

7.4 Discussion

Introduction

For normalization purposes, each muscle was expressed as a percentage of a maximal voluntary isometric activation recorded under standardized segment orientations. From a statistical perspective, the form of normalization procedure chosen was not overly critical for this study, as a repeated measures design was employed and data collection was carried out in one session. Therefore, factors such as signal impedance and electrode manipulation were controlled. However, a normalization process should consider posture (*i.e.* dynamic changes to segment orientation) and movement speed to derive more "mechanically" meaningful information (McGill, 1991; Mirka, 1991; Ng *et al.*, 2002). This approach would allow for better discussion of potential loading of a particular muscle during a pulling exertion. It is acknowledged that these issues are certainly critical when considering how EMG signals can be implemented in a model to predict individual or synergistic muscle forces, moments of force and/or spinal loading.

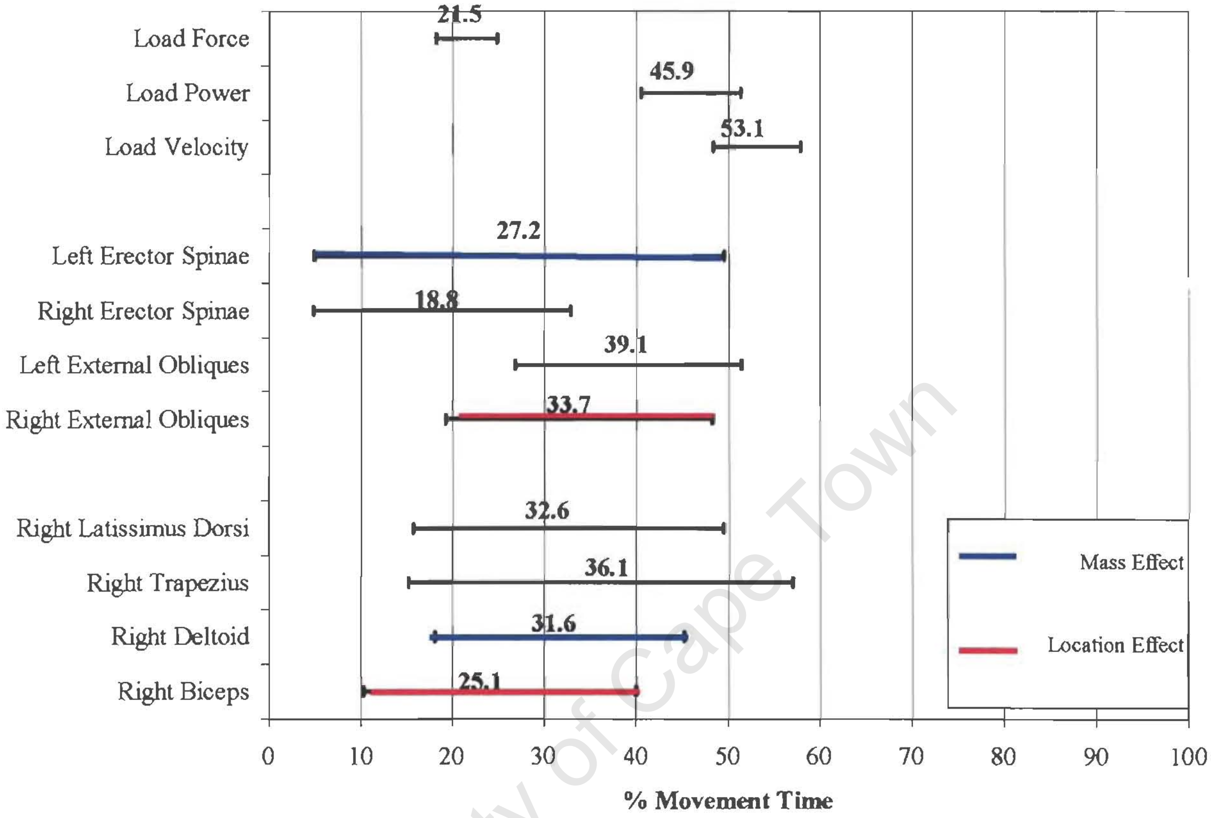


Figure 7.4: Variability, expressed as one standard deviation above and below the mean, of the time at which peak EMG activity occurred in during the pull exertion (expressed as a percentage of movement time). The numbers within the figure indicates the mean value.

Others have suggested that submaximal activations might be better suited for normalization purposes as this might reduce the variability in subject sincerity or motivation, as well as provide a more suitable methodological approach in studying persons with histories of musculoskeletal pain (Marras and Davis, 2001). Another under-explored approach would be to normalize to some baseline value, perhaps to one of the conditions thought to maximize or optimize performance under the specific experimental conditions (Bauer and Wittig, 1998). This could eliminate potential postural or movement speed effects although it could also limit the robustness of the data when attempting to compare it to previously published data. In consideration of these facts, employing these EMG data for inference of individual muscle loading would be overstating the empirical value of these experimental results. However, the normalization approach employed in this study does allow the kinesiological function of these muscles during the examined pulling activities to be assessed.

Assessing changes in muscle activations

There appeared to be a scaling effect of muscle activity with an increase in load. Given that there was a linear increase in load with condition, this finding was not surprising. However, relative changes in EMG intensity followed different trends between the eight muscles, suggesting that changes in posture affected the function of each muscle differently, although the outcome load kinematics remained unchanged. Ladin *et al.* (1989) have shown that even small variations in the external moments acting on a subject would have a significant impact on the recruitment strategies of the involved musculature. What was interesting was the relatively small SEM values. This indicates that the repeatability among the subjects was high.

Left and right erector spinae activity

As the feet were not symmetrically aligned and one-handed pulls were exerted, it might be expected that the demands upon, as well as the force producing capabilities of, the left and right erector spinae would be different with changes in pull location. In order to accommodate the exertions at the four pull locations the subject would have had to alter the amount of spine flexion/extension and axial rotation in order to complete the task (as illustrated in Figure 7.1), thereby changing the relative lengths of each muscle.

Figure 7.2 indicates that the relative activity of the left erector spinae increased consistently with increases in load. A rank order effect of Eye-In, Elbow-In, Eye-Out, Elbow-Out was observed for increasing levels of activity across all three loads (see Table 7.2), although a *post hoc* analysis indicated there was no significant difference in the activities between the Elbow- and Eye-In positions. Lateral pull exertions appeared to increase activity relative to the Elbow-In condition. In order to move the hands to these lateral locations, some amount of leftward axial rotation would be required. This would lengthen the left erector spinae putting it in a better position to produce force and thus contribute to the net pulling action. Van Dieen (1996) reported increases in contralateral paraspinal muscle activity for twisting actions of the trunk. He suggested that differences in the left and right activation patterns of the erector spinae may be necessary in order to create axial torque.

The EMG activations of the right erector spinae increased in the following ordinal manner for each load relative to the Elbow-In position: Eye-In, Elbow-Out and Eye-Out. Similar to the left erector spinae, lateral pull locations required greater activity compared to pulls closer to the anatomical sagittal plane. These increases in EMG activity were likely necessary to better stabilise against trunk rotation imposed by the lateral pull locations.

In comparison to the left erector spinae, the right erector spinae demonstrated relatively higher activations ($p < 0.001$), particularly for the 12 and 18% pull loads (refer to Figure 7.2). This might be expected as the loads were exerted on the right side of the body. Low back disorders have been associated with pulling exertions (Snook *et al.*, 1978; NIOSH 1981) and higher spinal loading has been estimated to occur with increases in asymmetrical paraspinal neuromuscular activation (Marras and Mirka, 1992; Marras, 2000). Given the observed increases in the magnitude of neuromuscular activity in erector spinae, it is likely that operators *in situ* engaged in similar repetitive pulling conditions examined in this protocol would likely be at risk for low back disorders. Limited research has been done on what levels of activity are likely to produce onset of muscular fatigue. However, in eight of ten conditions, the right erector spinae demonstrated activity levels above 30% of MVC values and it would be expected that this level of effort would lead to localised muscular fatigue under repetitive pull exertions.

Left and right external obliques activity

Several authors have reported that in order to maintain spine and trunk stability and postural equilibrium, trunk flexors, such as the external obliques, are active during lifting exertions (Marras and Mirka, 1993; Granata and Marras, 1995; Magnusson *et al.*, 1996; Cholewicki *et al.*, 1997; Marras *et al.*, 1998; Granata and Orishimo, 2001). While antagonistic co-contraction may lead to increased loading of the spine, *for more upright postures*, the benefits of increased stability seem to be favoured over modelled spinal loading in lifting activities (Granata and Marras, 2000).

Relatively high levels of muscle activity were recorded for both the right and left external oblique muscles, particularly in the heavier load conditions of pulling. In general, the right external obliques were more activated than the left external obliques ($p < 0.005$) and the magnitude of these differences increased with increasing load. Furthermore, in comparison to the Elbow In condition, there was a general decrease in the left external oblique activity for the Eye height exertions (see Table 7.2). Mirka *et al.* (1997) indicated that the external obliques displayed "selective" regional activation dependent upon the posture adopted during various axial isometric exertions. This seems to be consistent with the activation patterns during one-handed pulling activities.

The directional change of the external obliques demonstrated some trends. In all cases, increased external loads led to an increase in the level of activity for each muscle. There was an increase in the activity of the right external obliques particularly as the pull locations moved towards a more lateral sagittal plane. This activity was likely necessary to stabilise the trunk as it was extending during the pull exertion. The left external obliques demonstrated opposite trends to the right external obliques as the location of the pull was positioned more laterally. The level of activity from this muscle decreased as more lateral pulls were exerted, although not all conditions were significantly different. In terms of height of pull, the left external obliques again changed in different directions compared to the right external obliques. As the pull height was increased, the left external obliques demonstrated signs of reduced activity, while the right external obliques increased their activity.

More often than not, analyses of work related movements have focused on the net kinetic characteristics and paid little attention to those internal forces that influence the motion, such as co-activation of antagonistic muscles. Future research to examine the internal loads created within the operator during the execution of pulling activities will have to pay close attention to the influence posture has on levels of co-activation. Of particular interest are the opposing directional changes in the EMG activity that the left and right external obliques exhibit with changes in pull locations. In theory this should create asymmetrical loading profiles on the spine and increase the likelihood of injury to this anatomical region. However, relatively comparable findings from the lifting literature suggest that the external obliques may not be functioning antagonistically to the trunk extensors, but may be active in order to create or maintain stability in asymmetrical postures. Further research is required to determine what pulling postures may compromise the health of the spine because of high ventral muscle activations.

Trunk stabilization and the generation of axial rotation

This paper has reported on several studies which have examined trunk function during various well-controlled twisting and lifting activities. Comparing these to the present findings must be done with caution, although it is likely that trunk co-ordination strategies are shared amongst various manual materials handling activities. Marras and Mirka (1992) examined trunk musculature co-activation during realistic (in terms of manual materials handling activities) asymmetrical lifting exertions employing an isokinetic dynomometer. Levels of co-activation were recorded for submaximal torques about the lumbar spine. It is more desirable to examine co-activation strategies employing submaximal efforts as maximal efforts might serve to inhibit expressions of co-activation. In all conditions of trunk asymmetry (twisting to the right), trunk forward flexion and isokinetic speeds of movement increases in trunk musculature co-activation were measured, except for the external obliques for the more forward flexed trunk positions. They suggested that the increased co-activation would create increased resistance, stability or stiffness of the trunk. Ng *et al.* (2003) suggested that changes in the coupling torque and the variability in the rates of neuromuscular fatigue and levels of recruitment of trunk musculature could affect the internal loading and stability of the spine during submaximal, upright isometric axial rotations of the spine. Whether increases in muscle loading under these conditions is related to increased risk for musculo-skeletal injury requires further consideration (Granata and Marras, 2000). While these findings might explain the EMG results from the current study, one should keep in mind that single-handed pull exertions in themselves are asymmetrical in nature and likely load the spine in a manner different to pure trunk exertions in the axial directions.

One study has examined the effects of co-contraction on pulling activities. Thelen *et al.* (1996) reported that (two-handed) pull exertions through parasagittal planes resulted in greater predicted spinal compression loads compared to those exertions through the midline of the body. They suggested that pulling to the side of the body generates a twisting moment about the lumbar spine in addition to the moment due to the vertical height of the pull force vector. This necessitates larger antagonistic muscle co-contraction in order to stabilize better the trunk, thereby increasing the loading upon the spine. Their findings are consistent with the bilateral increases in both the erector spinae and external oblique muscles observed in this study when the location of the pull force is moved vertically and laterally relative to the centre of mass of the subject.

Latissimus dorsi activity

The latissimus dorsi extends, adducts and medially rotates the arm while pulling the shoulder down. Latissimus dorsi activity increased significantly by over 10 %MVC with increases in load and was found to be highly active in the heavier loads. Although there were no statistically significant changes in the recruitment magnitudes with changes in pull locations, this muscle demonstrated very little variability within load conditions. This suggests that the latissimus dorsi functioned similarly across all four pull locations within a load. Marras and Mirka (1992) and Tan *et al.* (1993) suggested that the latissimus dorsi acts as a synergist when an axial torque is created, particularly when the trunk assumes a forward flexed posture. This is the predominant posture in the current experimental protocol.

As the spine becomes more asymmetrical in the transverse plane, it might be expected that muscular control of trunk flexion and extension in the sagittal plane would shift from the erector spinae to the latissimus dorsi and external obliques (Marras *et al.*, 1990; Arnell *et al.*, 2000). As axial trunk rotation increases, the latissimus dorsi gains a biomechanical advantage as the muscle is stretched and can better optimise the elastic properties of the muscle-tendon unit. In this experiment, trunk asymmetry was likely to have occurred because of the asymmetrical foot positions and the nature of lateral pull conditions. This could have placed demands upon the latissimus dorsi to assist not only in trunk control, but also to move the shoulder complex during the pull exertion.

Trapezius activity

The relationship between pulling activities and musculoskeletal disorder for areas of the body other than the lower back have not been extensively studied. Hoozemans *et al.* (1998) have suggested that the shoulder region may also be at risk for injury as a result of pulling activities when the exertions occur above acromion height or are performed in asymmetrical postures. The trapezius, which elevates or depresses, rotates, adducts and stabilizes the scapula, demonstrated significant differences in EMG recruitment (see Figure 7.3) with changes in pull posture. As the pull origin moved laterally from the sagittal plane dissecting the gleno-humeral joint and as the arm was abducted trapezius recruitment magnitudes were increased. This increasing level of recruitment likely represents the reduced force producing capacity of the muscle as it shortens due to the hand moving laterally and superiorly. In eleven of twelve conditions, the trapezius functioned at activity levels greater than 30% of its MVC and in the majority of the conditions was recruited to levels greater than 40% of its MVC. As suggested by Hoozemans *et al.* (1998), it is likely that repeated overhead, awkward pulling postures would stress and fatigue the trapezius muscles and possibly lead to overexertion injuries. Future research should attempt to gather kinematic data on the shoulder complex and relate its movements to other parts of the anatomy, particularly that of the trunk.

Biceps brachii activity

The variability in how subjects recruited the biceps brachii was quite high (Figure 7.3). While a significant difference was reported between pull locations, *post hoc* analyses indicated that only the Eye-In activity was greater than the Elbow-In location (see Table 7.2). This may reflect the nature of recruitment of biarticular musculature. As this muscle crosses both the elbow and shoulder joints, it has a greater degree of freedom to accommodate postural changes associated with pull attempts at diverse locations within a reach envelope, particularly as the pull origin moves superiorly. Although it appears, from a neuromuscular perspective, the contribution of this muscle was consistent across pull locations, it is also true that the amount of between-subject variability was likely high.

Understanding how load sharing strategies differ between mono- and multi-articular musculature remains important to understanding human movement coordination and injury potential.

Deltoid activity

The deltoid had the largest relative activity across loads and pull positions of all the eight muscles examined. This would likely put this muscle at the greatest risk for onset of fatigue during repetitive or sustained pull efforts. The deltoid demonstrated no significant changes in muscular activity with changes in pull location. It might have been expected that the activity in the deltoid would be greater for the lateral pull exertions when the upper arm is adducted (refer to Figure 7.1). While there seemed to be a trend in the data that suggested more lateral pull locations required more deltoid activity it might be more appropriate to conclude that the deltoid acted to stabilise the arm during all pull events.

Load kinematics and peak muscle activity timing effects

As reported in the results section, there were no significant differences in the movement times across the 12 experimental conditions, and so normalizing these data in time should not result in significant temporal distortion between experimental conditions. Load kinematics displayed very little variability in the time at which peak velocity, force and power occurred within the pull exertion. In contrast, the variability of the temporal muscle recruitment patterns were considerably larger (see Figure 7.4). This suggests that there is some degree of freedom, from a neuromuscular perspective, in which a subject can coordinate a net pull force on a load handle for various locations in the frontal plane. There were some predictable trends in the muscle sequencing. The erector spinae, both left and right, demonstrated the earliest activation in the movement cycle of the trunk muscles examined. This would suggest that subjects tended to exploit the inertial properties of the trunk early in the movement cycle as a means of producing load momentum. The peak activity in the left erector spinae occurred earlier in the pull cycle as pull mass increased. Van Dieen (1996) reported that erector spinae activity was necessary to initiate axial rotation of the trunk. Van Dieen (1996) also reported that the erector spinae muscle on the contralateral side to the direction of the twist was necessary at larger angles of twist. Similarly, Pope *et al.* (1987) reported that the magnitude and direction of pre-rotation of the trunk had an influence on both trunk musculature recruitment and torque production in axial twisting efforts. Marrying these EMG data with thoracolumbar spine kinematics simultaneously collected in the previous chapter will considered in the concluding chapter. The amount of trunk asymmetry during the execution of the pull exertion likely contributed to the large variability in when subjects displayed peak activity for this muscle.

The effects of load magnitude on the variability in the time of peak activity in the erector spinae may reflect the numerous coordination strategies with which the load could be moved. With light loads, perhaps arm strategies predominate early in the movement, while heavier loads required early contributions through trunk motion.

As discussed earlier in this section, the external obliques became active to assist in trunk rotation and improve trunk stability. The right external oblique displayed an effect due to location of the pull origin. Specifically, the peak activation occurred earlier in the movement cycle for the Eye-In and Eye–Out locations. Elevating the arm would lengthen the muscle, creating a pre-tensile stretch and possibly reducing the amount of electro-mechanical delay.

The time of peak activation was not affected by mass or pull location for either the latissimus dorsi or the trapezius muscles. Both seemed to be active most over similar periods for a pulling task. The pull mass affected the timing for the deltoid. As load increased, the peak activation occurred later in the movement cycle. The deltoid is important in stabilizing the shoulder joint, so these results are not unexpected. The timing of peak activation of the biceps brachii demonstrated a location effect. Eye level conditions had earlier peak activations and likely reflect postural adjustments made by the upper arm segments and concomitant changes in biceps muscle length to acquire the load handle.

7.5 Conclusions

The underlying assumption in most studies employing EMG analysis techniques is the existence of constant or predictable relationships between EMG activity and muscle force (Basmajian and De Luca, 1985). While the exact relationship between mechanical force output and muscular activation remains unknown, large changes in activity likely reflect a change in muscle function for similar experimental conditions. By applying statistical findings conservatively, it becomes reasonable to make conclusions about muscle function from EMG profiles. Thus, the following conclusions should only be considered in light of these limitations and assumptions.

It is suggested that the muscles examined in this study could all be considered important in the execution of upright pull forces and should be considered as necessary input factors in future EMG/biomechanical prediction models. Most notable is the level of, and asymmetry in, recruitment of the external obliques. Those models that do not consider co-activation would likely under-predict the loads acting on the spine.

While pull location led to significant differences in %MVC activity in 6 of 8 muscles examined, those muscles not affected demonstrated high levels of constant activity (latissimus dorsi and biceps brachii). This suggests that generalised fatigue about the shoulder joint may be likely to occur in repetitive exertions under higher loads.

Although there were 12 pull conditions, there was no significant variability in the self-selected pull times within or between subjects. It is interesting that all subjects exhibited similar movement times. Future research should attempt to establish if there are kinematic or kinetic relationships between segmental motions and whether these are inherent movement patterns of pulling activities.

Loads above 6% of lean body mass promote significant increases in muscular activity. With respect to the subjects employed in this study, this equates to an absolute mass above 4.3 kg (+/- 0.5 kg). It is thus recommended that workstations requiring repetitive pulling exertions on loads greater than these should be re-assessed for their potential to induce muscular fatigue.

It was hypothesized that as the origin of pull becomes located towards more extreme locations of the reach envelope the magnitude of neuromuscular recruitment increases. It is apparent that as the pull origin in the frontal plane is moved laterally and, in some cases, superiorly, the activities of the muscles increased. These increases in activities could be a result of: (1) a change in demands upon these specific muscles; (2) increases in the speed at which the muscles were shortening; or (3) a change in the operating lengths of the muscles due to the different pull locations about the frontal plane. Further research, employing a kinetic model, is required to determine if there are changes in musculo-skeletal demands that might increase the risk for overexertion injuries during repetitive, single-handed pulling.

Chapter 8

Effect of the Reach Distance on the Execution of One-Handed Submaximal Pull Forces

This study examined the effects of reach distance on the lumbar spine kinematics and electromyographical activities (EMG) of eight selected muscles of the trunk and shoulder during submaximal horizontal pulling exertions (12% of lean body mass) all located at elbow height. Eleven healthy male volunteer subjects were asked to pull on an isoinertial load located at varying distances (10, 15, 20, 25, 30, 35 and 40% of subject stature) from the frontal plane containing the load handle. Magnitudes of trunk extension in the sagittal plane, as monitored by a Lumbar Motion Monitor, increased significantly, demonstrating increasing values as reach distance increased. While trunk velocities and accelerations for axial rotation did not change with condition, measured values are consistent with those associated with in situ measures of lifting tasks associated with a high incidence of low back disorders. LMM kinematic data for lumbar extension in the longer reach conditions also exhibited magnitudes comparable to occupations identified to be at high risk for development of low back pain during lifting activities. EMG data revealed increasing erector spinae activity as reach distance increased and this muscle group was found to be co-active with external oblique muscles during the exertion. Shoulder complex muscles were found to be highly active in all conditions, but only the trapezius and deltoid demonstrated significantly decreasing activity as pull reach increased. Results from this study suggest that the strategy a subject employs to execute a pull on a fixed load changes with a change in length of reach. It seems that executing a pull under conditions such as those simulated in this study could be optimized if the subject stood with the front toe at a distance of approximately 25% of stature from the frontal plane containing the load handle. These data provide some direction in positioning the operator within a workstation demanding pull force exertions.

8.1 Introduction

A popular ergonomics intervention strategy to reduce the stresses acting on the lower trunk is to minimise the amount of trunk flexion and rotation required for a manual materials handling (MMH) activity (NIOSH, 1981). It is well known that greater amounts of trunk flexion will increase the moment arm of the head-arms-trunk segment relative to the lumbar spine thus increasing the counteractive forces required of the erector spinae to create trunk extension. Increased trunk flexion will also cause the body's centre of mass to move anteriorly within the base of support, decreasing the inherent stability of the system. However, a certain amount of trunk flexion can be advantageous from a mechanical perspective, as this would allow the operator to take advantage of the high inertial properties of this segment and generate momentum in the extension direction to apply against the load (MacKinnon and Li, 1998).

From an injury prevention perspective it may seem advantageous to eliminate or minimise exertions by the trunk musculature during MMH tasks. However, this intervention strategy may likely predispose other anatomical structures to higher risks for musculo-skeletal injuries, particularly the small, gracile muscles of the upper extremity (Hoozemans *et al.*, 1998). A better understanding of how an operator creates motive forces will assist the ergonomist in designing work situations that reduce stresses on parts of the body likely vulnerable to injury.

In one-handed, submaximal pulling activities the forces required to move the load are not likely produced from trunk motion alone, but with contributions from other parts of the body. The upper extremity plays an important role in exerting horizontal pulling forces (Hoozemans *et al.*, 1998) but more insight into the kinesiological strategies employed by an operator under varying pulling situations is still required.

Researchers examining MMH activities have attempted to identify those factors that impose higher mechanical demands on the spine and are assumed to be related to the aetiology of MMH-related injuries. For example, studies on lifting exertions, have examined the effects of load mass, load size and shape, location of the load relative to the operator and movement frequency on the forces and moments acting upon the operator (*e.g.* NIOSH, 1981). This experimental approach provides support for recommendations regarding how these factors should be eliminated or controlled to reduce the stresses experienced by the operator. While several authors have promoted guidelines for safe lifting (*i.e.* NIOSH, 1981; Snook and Ciriello, 1991; Shoaf *et al.*, 1997) there is limited information regarding safe or allowable limits for stationary pulling activities.

Similar to lifting activities, task-related factors such as strength capacity (Dempster, 1958; Daams, 1993), operator posture (Chaffin *et al.*, 1983; Fothergill *et al.*, 1991), and exertion location (Ayoub and McDaniel, 1974; MacKinnon, 1998) have been examined to assess the force producing capacity of the operator or to estimate the loads acting on the body (Kumar *et al.*, 1995; Lee *et al.*, 1991) during pulling activities. Much of the research in this regard has been done under strictly controlled laboratory conditions, primarily to ensure the quality of information needed as input dimensions for predictive kinetic models.

The purpose of this study was to evaluate how varying the distance of a subject from the frontal plane containing the origin of pull would affect the manner in which a pull exertion is performed. Specifically, measures of activities of trunk and shoulder musculature and trunk kinematics were obtained to determine if the strategy for creating a pull was altered as a subject moved away from the plane containing the origin of pull. Such empirical data should provide some insight into how workstations should be designed, or how subjects should be positioned within workstations, to reduce the demands of single-handed pull exertions. It is hypothesized that as the subject moves further away from the frontal plane containing the origin of pull there will be a concomitant increase in the activities of the monitored muscles and the lumbar motion monitor kinematics.

8.2 Methods

Eleven healthy male university students volunteered to participate in this study. Subjects were free of any current or past musculoskeletal injuries. Subject selection was limited to those who reported right hand and right lower limb dominance. All subjects reported an active lifestyle and all engaged in some form of regular weight training programme. It was considered advantageous to employ subjects who trained regularly, as these would likely reflect the strength characteristics of labourers better than more sedentary individuals.

After the experimental protocol was explained and the subject was offered an opportunity to ask questions, informed consent was obtained. This study was given formal approval by the Departmental Ethics Committee. Subjects were then given an opportunity to become familiar with the experimental conditions. During this session, basic anthropometric measures were obtained (see Table 8.1). Subjects were requested to return the following day to participate in the formal data collection session.

Experimental Conditions

This study examined pull exertions originating through a horizontal plane that coincided with the subject's elbow height from the floor and a sagittal plane that was defined by the location of the gleno-humeral joint centre when the arm is held relaxed at the subject's side. This pull force location has been identified as near optimal for creating maximal isometric pull forces

(MacKinnon, 1998). Each subject was required to execute a one-handed pulling action against a load of 12% of lean body mass, through a horizontal displacement equal to 20% of the subject's stature. Load and displacement magnitudes were based on MacKinnon (1999) and were considered to be well within levels of submaximal effort of an average subject. A metronome was employed to establish a pulling frequency of 15 cycles per minute.

Table 8.1: Subject anthropometrics.

Variable	Mean	SD	CV
Age (Yrs)	23.5	2.3	9.8
Stature (cm)	181.6	4.1	2.3
Elbow Height (cm)	113.7	2.6	2.3
Mass (kg)	81.7	13.2	16.2
*Body Fat (%)	13.3	6.6	49.7

*body density and percent body fat were determined following the procedures described in Jackson and Pollack (1978) and Siri (1956).

The feet were standardised in an asymmetrical orientation. These foot orientations were based on previous research (MacKinnon, 2002). The relative orientation between the two feet were kept constant throughout the experiment (refer to Table 8.2), although the left toe was re-positioned between 10 and 40% of subject stature, in 5% increments, from the frontal plane in which the pull exertion was initiated (*i.e.* 7 separate experimental conditions). These positions were demarcated on a slip resistant surface. This supporting surface could then be manipulated into a correct location to accommodate each condition. Figure 8.1 (a and b) illustrates two of these reach locations.

Spine Kinematics

A Lumbar Motion Monitor (Chattecx Corporation, USA) was employed to assess thoracolumbar kinematics in three planes: flexion-extension movements in the sagittal plane, rotation about the longitudinal axis and lateral bending within the frontal plane. Angular displacement-, velocity- and acceleration-time profiles were collected or derived for each movement plane. Detailed description of the measurement device may be found in Marras *et al.* (1992).

Table 8.2: Subject-relative experimental variables.

Variable	Mean	SD
12% Load (kg)	8.4	0.9
Load Displacement (cm)	81.7	1.9
Distance Increment Between Conditions (cm)	9.1	0.2
Toe-to-Toe Distance in Sagittal Plane (cm)	45.4	1.0
Toe-to-Toe Distance in Frontal Plane (cm)	18.2	0.4
Left Foot Angle Relative to Right Horizontal (deg)	55.0	-
Right Foot Angle Relative to Right Horizontal (deg)	35.0	-

(a) Distance of 10% from frontal plane

(b) Distance of 40% from frontal plane

Figure 8.1: Representative postures for the nearest (a) and furthest (b) reach distance.

Muscular Activity

A ME3000P (Mega Electronics Ltd, Kuopio, Finland) unit was employed to collect the electromyographic (EMG) activity of the following muscles: left and right erector spinae (at the level of the fourth and fifth lumbar vertebrae), left and right external obliques and the trapezius, latissimus dorsi, deltoid and biceps brachii from the right side of the body. The EMG unit was connected to the communications port of a personal computer, via an optic cable, for online data collection. Each channel was sampled at 1000 Hz, band-pass filtered between 20 Hz and 500 Hz, amplified (differential amplifier, common mode rejection ratio ≥ 130 dB, gain x 1000, noise ≤ 1 μV) and analogue-to-digitally converted (12-bit), and stored on personal computer for further analysis. The amplification of the biological signal was done at the grounding electrode site, which effectively minimises signal artifacts caused by movements and external noise.

The raw EMG signals were full-wave rectified and low-pass filtered at 4 Hz. The mean voltage and the relative time of occurrence (% cycle) of the peak amplitude for each pull exertion for each muscle and condition was determined. The amplitude from a manually resisted maximal voluntary contraction (MVC) for each muscle was collected for two periods of five seconds. To elicit the MVC, relevant segments were placed at the mid-range of motion of the joint and manually resisted. The largest mean MVC of the two isometric contractions was selected to normalise the mean EMG values for each pull exertion.

Experimental Design and Data Collection Protocol

Prior to data collection, Ag/AgCl electrodes with a recording surface of 100 mm^2 were applied to the mid-belly of each muscle in a bipolar configuration in accordance with the manufacturer's suggested guidelines. The distance between the centres of the recording surfaces of active electrodes was standardised to 15mm and the ground electrode was placed off the belly of the muscle of interest, approximately 100mm away from the recording site. Electrode preparation included shaving the body hair from the recording sites and cleaning the skin with alcohol swabs. The electrodes and wires were secured to the subject using adhesive tape. No electrode manipulation occurred during the data collection period.

Following electrode preparation, the Lumbar Motion Monitor (LMM) harnesses that best fit the subject were applied to the subject and positioned so that the exoskeleton was mounted in a symmetrical position relative to the subject's trunk. Prior to the start of each trial, the subject was asked to position himself in a military-style "attention" position in order to calibrate the LMM. Thus, the displacement data of the exoskeleton is relative to this position.

The subject was then asked to stand on the slip resistant surface that demarcated the standardised foot positions. The feet were aligned to the investigator's satisfaction. An En-Tree isoinertial pulley system (Enraf Nonius B.V., Holland) was employed to provide resistance against the pulling action. The handle height and load were determined based on the prescribed subject anthropometric characteristics. The subject was provided ample time to familiarise himself with the data collection protocol and attempt all conditions prior to actual data collection. Data collection did not commence until both subject and experimenter were satisfied that the subject could competently execute the task.

The measured pull cycle began when a non-zero load velocity was detected by the En-Tree system and ended when the load velocity again returned to a zero value. Data from the LMM and the EMG unit were synchronised with the En-Tree system upon commencement of data collection of each trial using a switch that interrupted data transmission through the communications port of the computer connected to each of the measurement devices. The subject was instructed to exert a minimum of 10 pull cycles. He was given a minimum of 150 seconds of rest between each trial in order to minimise the effects of fatigue. The seven experimental conditions were presented to the subject in random order.

Statistical Analyses

A one-factor analysis of variance for repeated measures was used to assess differences across the seven experimental conditions. In each instance, homogeneity of variance was confirmed. The Tukey method was employed for *post hoc* analyses using a 95% confidence interval for specified linear combinations.

8.3 Results

Five consecutive pull cycles were selected and averaged for subsequent analysis for each experimental condition for each subject. It has been reported that five repeated measurements were sufficient to obtain an unbiased estimate of the demands imposed on the subject (van der Beek *et al.*, 1999).

Load Kinematics

As expected, there were no significant differences ($p < 0.001$) in the pull cycle duration within and between subjects as a metronome was employed in this experimental protocol. There was no effect of reach distance on the time of maximum load velocity, force and power during the pull cycle.

EMG Measurements

Table 8.3 contains the mean (and standard error of the mean) muscle activities normalised by the MVC's across all subjects. The ANOVA indicated that only the left ($p=0.009$) and right ($p=0.004$) erector spinae (ES), trapezius ($p<0.001$) and deltoid ($p<0.001$) were significantly affected by a change in condition. Figure 8.2 (a and b) illustrates the normalised activities of those muscles found to be significantly affected by condition, including figure notes indicating the results obtained from the *post hoc* analysis.

The EMG-time profiles were examined to determine if there was an effect of condition upon the time when the maximum activity occurred during the movement cycle. Only the trapezius ($p<0.001$) and deltoid ($p<0.001$) muscles demonstrated a significant effect. As the subject increased the reach distance, the time of peak activity occurred later in the movement cycle for both muscles (see Figure 8.3).

A correlation between the occurrence of peak EMG activities of the trapezius and deltoid was performed. A significant correlation ($r = 0.942$) was calculated between these two variables (see Figure 8.4).

LMM Measurements

Table 8.4 includes a summary of the mean (and standard error of the mean) LMM variables collected for the sagittal and twisting planes. Results from the ANOVA are indicated in the far right column. Data from the lateral plane are not included as it was decided that the range of motion in this direction was too small to reflect any practical significance. In all cases, the mean range of bending to the left or right was no greater than 5 degrees in either direction and the maximum velocity and acceleration values in these directions were comparably small with respect to those measured for lifting activities thought to place the operator at a higher risk for developing low back disorders (Marras *et al.*, 1993; Marras *et al.*, 1995).

The LMM kinematic-time profiles were examined to determine if there was an effect of condition upon the time when the maximum value occurred during the movement cycle. Only the time at maximum extension velocity of the trunk in the sagittal plane ($p=0.024$) proved to be significantly different due to condition. Figure 8.5 illustrates that as the subject moved away from the frontal plane, the earlier in the movement cycle maximum back extension velocity occurred.

Correlations between time of maximum trunk extension velocity and those muscles exhibiting a timing effect with condition (*i.e.* trapezius and deltoid) were considered. There were moderate correlations between the occurrences of peak values of the trapezius EMG activity and trunk extension velocity ($r=0.864$) and deltoid EMG activity and trunk extension velocity ($r=0.792$). Figure 8.6 (a and b) illustrates these relationships.

Table 8.3: Mean (standard error of the mean) muscle activity as a percentage of maximal voluntary contraction.

Condition	Left ES	Right ES	Right EO	Left EO	Trapezius	Lat. Dorsi	Deltoid	Biceps
10%	7.0 (1.5)	10.6 (2.0)	7.8 (1.7)	15.1 (5.2)	52.5 (4.3)	29.6 (5.7)	73.2 (9.1)	22.8 (4.5)
15%	7.9 (2.0)	10.7 (1.8)	7.7 (1.4)	12.7 (3.3)	50.1 (5.8)	29.0 (7.3)	70.8 (4.3)	24.6 (4.7)
20%	8.8 (1.8)	11.5 (1.7)	7.0 (1.5)	10.6 (3.1)	49.1 (7.3)	30.0 (6.4)	68.8 (6.0)	22.4 (4.8)
25%	9.9 (1.9)	13.3 (2.3)	7.5 (1.8)	9.2 (3.7)	44.2 (6.9)	30.8 (6.4)	57.3 (4.2)	25.6 (5.9)
30%	12.3 (2.8)	15.2 (2.6)	6.8 (1.5)	5.7 (1.8)	32.7 (4.2)	37.1 (7.6)	43.1 (4.5)	20.6 (3.2)
35%	14.5 (1.7)	19.2 (2.9)	6.7 (1.6)	4.7 (1.8)	29.8 (5.1)	43.6 (7.0)	41.1 (5.6)	21.9 (4.0)
40%	17.7 (2.4)	26.1 (5.6)	6.8 (1.5)	5.8 (1.8)	21.9 (3.7)	45.2 (6.5)	26.7 (4.4)	16.2 (3.0)

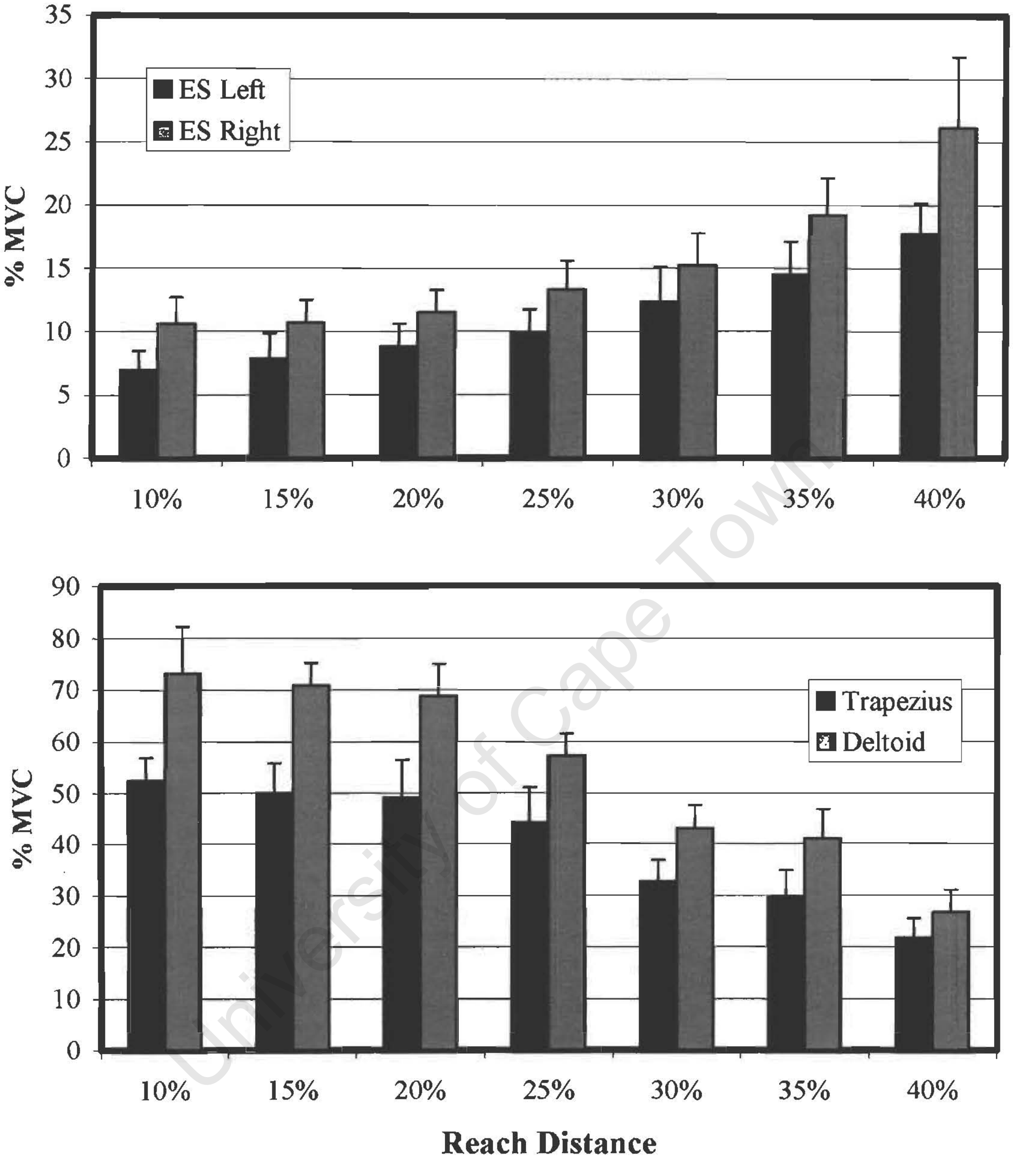


Figure 8.2: Mean (and standard error of the mean) EMG data, expressed as a percentage of maximum voluntary contraction (%MVC), compared for seven different reach distances (expressed as a percentage of stature). When performing *post hoc* comparisons with α = 0.05, the following differences were found for the four muscles: (1) Left ES – 10%/15% different to 40%; (2) Right ES – 10%/15%/20% different to 40%; (3) Trapezius – 10%/15%/ 20% different to 40%; (4) Deltoid – 10%/15%/20% different to 30%/35%/40%; 25% different to 40%.

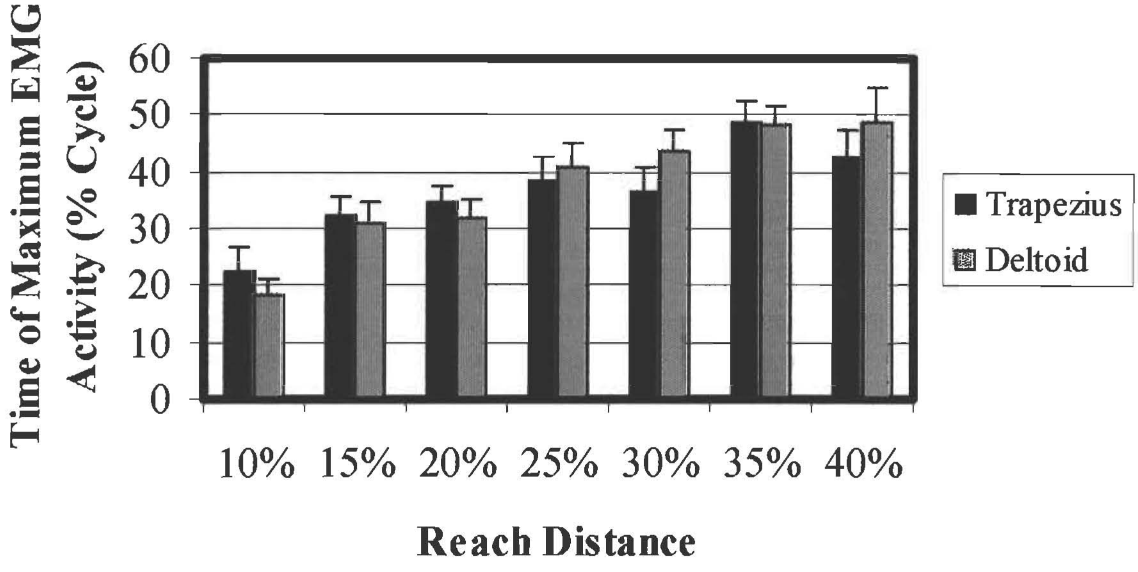


Figure 8.3: Mean (and standard error of the mean) time of maximum EMG activity (% of the pull cycle). When performing *post hoc* comparisons at $\alpha < 0.05$, the following within muscle differences were found: (1) Trapezius – 10% reach distance was significantly earlier than the rest of the conditions; (2) Deltoid – 10% reach distance was significantly earlier than the rest of the conditions, otherwise all conditions were significantly different *except* when compared to the next closest or furthest reach distance.

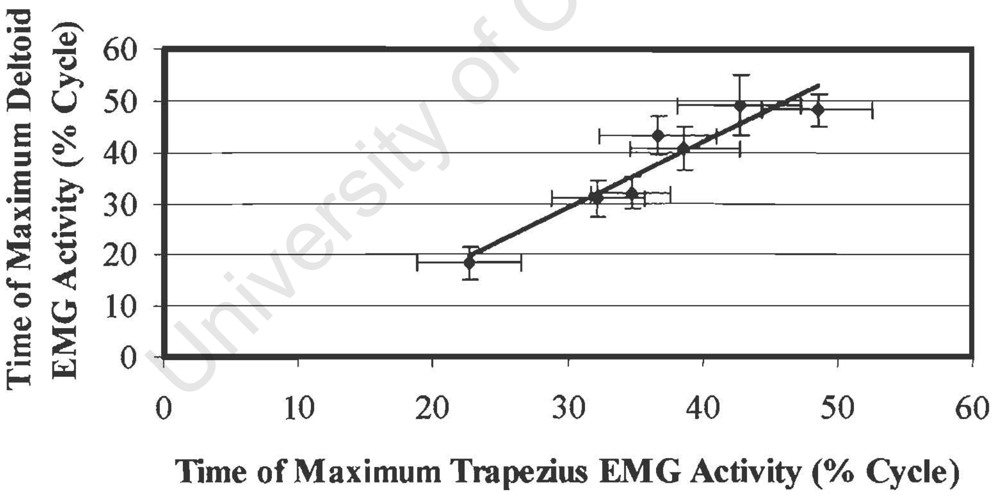


Figure 8.4: Linear correlation (with standard errors of the means for each coordinate) of maximum EMG activity (% of the pull cycle) between the trapezius and deltoid muscles.

Table 8.4: Mean (and standard error of the mean) kinematic variables obtained from LMM.

	Condition							
	10%	15%	20%	25%	30%	35%	40%	p
Sagittal Plane								
Flexed Starting Position (deg)	13.6 (1.9)	16.1 (2.4)	20.0 (2.9)	25.0 (2.7)	30.2 (3.6)	38.3 (4.2)	46.4 (3.4)	<0.001
Finishing Position (deg)	12.4 (2.4)	15.0 (2.6)	16.2 (3.1)	22.1 (3.9)	26.4 (3.8)	23.4 (5.8)	31.4 (6.2)	0.035
Extension Range of Motion (deg)	1.2 (1.3)	1.1 (1.6)	3.8 (1.2)	2.9 (2.9)	3.8 (3.7)	14.9 (6.4)	15.0 (6.3)	ns
Maximum Extension Velocity (deg.s^{-1})	24.7 (5.2)	21.7 (3.8)	36.8 (6.7)	55.2 (9.4)	71.6 (12.3)	89.7 (11.1)	95.0 (21.2)	<0.001
Maximum Acceleration (deg.s^{-2})	184.2 (40.9)	162.3 (18.4)	213.2 (41.5)	410.7 (51.9)	540.4 (36.0)	525.1 (29.8)	613.2 (57.0)	<0.001
Maximum Deceleration (deg.s^{-2})	103.9 (24.9)	96.0 (24.8)	98.3 (11.7)	161.5 (24.4)	245.4 (30.9)	296.8 (39.2)	403.0 (81.8)	<0.001
Twisting Plane								
Starting Position (deg)	14.3 (1.4)	17.5 (1.5)	20.1 (2.5)	24.0 (0.9)	26.4 (1.4)	25.5 (3.6)	26.9 (1.9)	<0.001
Finishing Position (deg)	5.6 (2.8)	9.1 (3.2)	11.9 (3.5)	18.5 (2.0)	20.6 (2.4)	16.5 (4.4)	19.1 (3.0)	0.010
Twist to Right Range of Motion (deg)	8.8 (3.4)	8.5 (3.5)	8.2 (2.4)	5.5 (2.4)	5.7 (2.7)	9.0 (6.6)	7.8 (3.3)	ns
Maximum Twist Right Velocity (deg. s^{-1})	60.1 (8.8)	55.0 (9.5)	59.8 (5.0)	53.8 (10.9)	54.5 (13.0)	50.6 (12.2)	45.4 (11.4)	ns
Maximum Acceleration (deg. s^{-2})	336.0 (31.5)	300.1 (29.1)	285.9 (53.5)	326.5 (41.9)	363.3 (55.8)	327.9 (41.9)	278.1 (32.3)	ns
Maximum Deceleration (deg. s^{-2})	127.5 (37.8)	101.0 (34.8)	117.3 (25.7)	64.1 (10.0)	76.7 (7.5)	173.5 (26.7)	111.8 (24.2)	ns

Note: ‘ns’ indicates not statistically significant

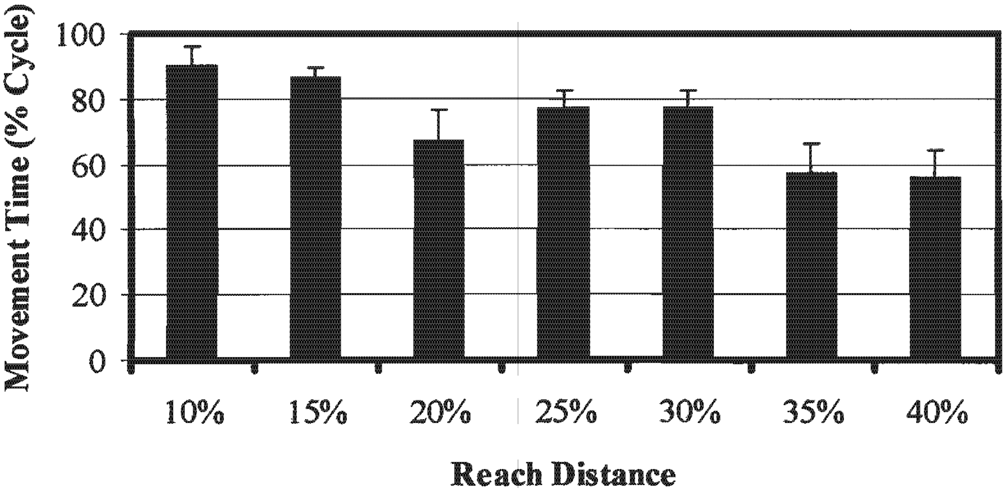
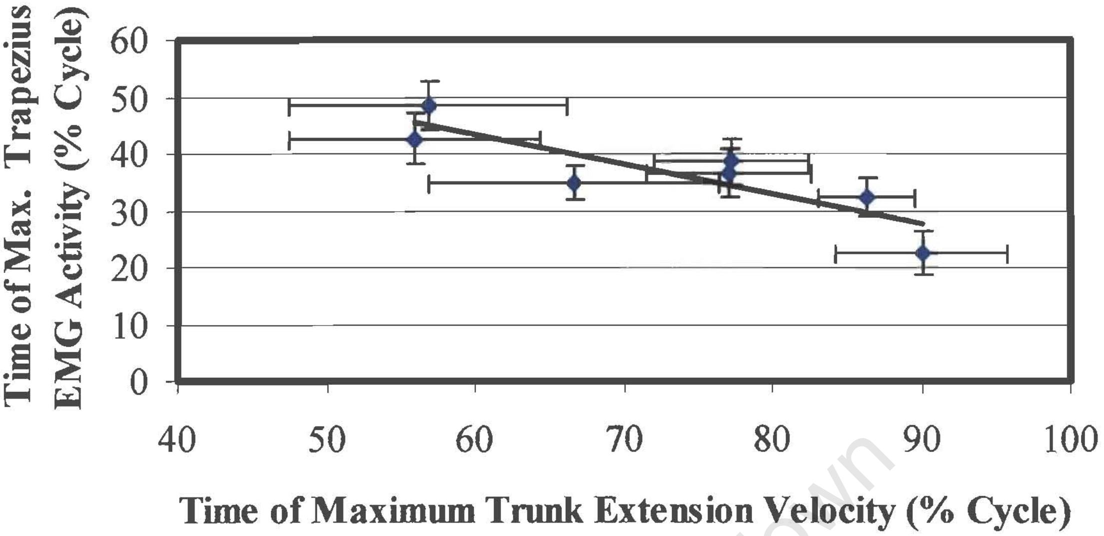


Figure 8.5: Mean (and standard error of the mean) time of maximum trunk extension velocity (% of the pull cycle). When performing *post hoc* comparisons at $\alpha < 0.05$, the 10, 15, 25 and 30% reach distances were significantly larger than the 35 and 40% reach distances.

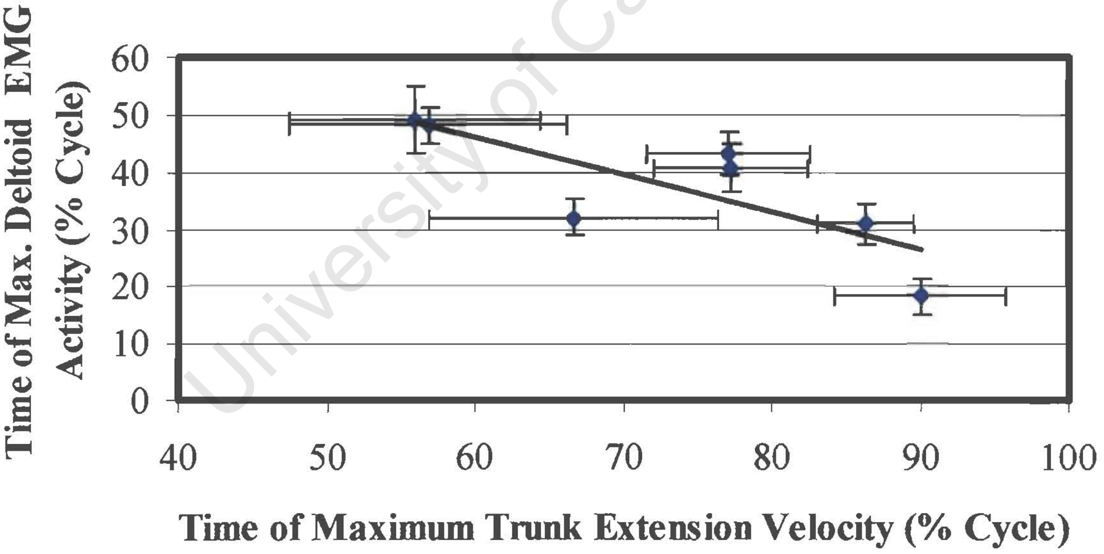
8.4 Discussion

In assessing job-related demands, those tasks that require greater amounts of trunk displacement, rates of trunk motion and activity in those muscles responsible for the movement are likely to impose higher demands on the spine and, by implication, increase an operator's risk for developing low back disorders. However, merely correcting for poor back mechanics may consequently place other parts of the body at a greater risk for injury. In tasks that allow for a high degree of freedom of movement, it is important for the Ergonomist to optimise the design of a workstation in order to minimise the stresses on all involved anatomical structures.

By increasing the distance of the operator from the frontal plane that contained the pull origin, both spine kinematics and activity of selected musculature changed. As expected, subjects were required to increase flexion of the spine in order to reach the load handle. Because the length of pull was standardised (*i.e.* 20% of subject stature), the final trunk position also demonstrated increasing amounts of trunk flexion as the subject moved away from the frontal plane, although the differences between conditions were smaller compared to differences in the starting trunk orientation. This could be accounted for by a reduced amount of axial rotation (to the right) for some conditions (see Table 8.4) as the length of reach increased or scapular protraction during the pull cycle. Unfortunately, shoulder and elbow joint kinematics were not measured in the study.



(a)



(b)

Figure 8.6: Linear correlation (with standard errors of the means for each coordinate) of time of maximum trunk extension velocity (% of the pull cycle) and the maximum EMG activity (% of the pull cycle) of the (a) trapezius and (b) deltoid muscles.

The magnitudes of trunk extension velocity and acceleration increased with increasing distances (see Table 8.4). This trend was consistent with the EMG activity of both the left and right erector spinae (see Table 8.3 and Figure 8.2 (a)). *Post hoc* analyses indicated that the 10, 15 and 20% conditions were significantly different than the 30, 35 and 40% conditions for both the trunk extension velocities and accelerations and level of activity in the erector spinae complex. While not significant from a statistical perspective, concomitant decreases in external oblique activity were observed as reach distance increased. Tan *et al.* (1993) suggested that external oblique activity would likely decrease because these muscles shorten as the amount of forward flexion is increased, putting them in a less than desirable position to produce force. The time of maximum trunk extension velocity occurred earlier during the pull cycle as the length of reach increased (see Figure 8.5). With maximum extension velocity occurring earlier in the pull cycle for longer reach distances, coinciding with increasing trunk extension velocity magnitudes, the subject is likely taking advantage of opportunities to exploit the inertial properties of the trunk. It was surprising that the timing of the maximum activity of the erector spinae did not change in a similar fashion to the extension kinematics. The peak activity for the left and right erector spinae occurred at 21.4% (SD=11.7%) and 15.4% (SD=12.9%) into the pull cycle respectively. It seems that is was the significant increases in activation of the paraspinals which were most responsible for the earlier occurrence of peak extension velocity during the movement cycle as reach distance increased.

In comparison to sagittal plane trunk kinematics reported by Marras *et al.* (1993, 1995) for lifting activities associated with a high incidence of low back disorders, the magnitudes observed in several of the experimental conditions were considerably higher, suggesting that if these trunk kinematics were observed *in situ*, these types of pulling reaches might predispose an operator to a higher risk for developing low back pain. Even the average load handled reported by Marras *et al.* (1995) is similar to the mean pull loads employed in the current study (88.40 ± 75.43N vs 82.4 ± 8.8N respectively). Comparisons to Marras *et al.* (1993, 1995) must be made with caution. The statistical analyses of the retrospective findings by Marras and Colleagues are based on monitored **lifting** activities measured *in situ* while the thoraco-lumbar kinematics reported in this study are derived for **pulling** actions created under more controlled laboratory conditions. However, given the importance several authors have placed on the association between trunk kinematics and risk for low back pain perhaps it isn't completely unreasonable to make these comparisons (Marras *et al.*, 1995; Norman *et al.*, 1998). Another important consideration in comparing these manual materials handling activities is the fact that lifting loads tend to create higher relative compressive loads, while pull exertions tend to create larger shear components at the lumbar spine. All things being equal (*i.e.* load magnitude and spine kinematics), it is likely that pulling actions have greater potential for causing low back pain than lifting actions. However, further research examining low back mechanics during pulling exertions is required to justify the preceding statement. Certainly, these findings support the need to relate trunk motions and incidence of low back pain in those occupations requiring the operator to perform regular pulling exertions.

Norman *et al.* (1998) estimated the odds ratios for developing low back pain associated with various trunk kinematic measures, such as trunk flexion and velocity in the sagittal plane in a study of automotive workers. They concluded that sagittal plane trunk kinematics are not merely surrogates of spinal loading estimates from biomechanical models, but are independently related to risk for low back pain. As such these parameters must be more closely scrutinized as predictors of spine loading as opposed to being limited to primary prediction model inputs.

While there were no statistically significant differences in the amount of twisting velocity and accelerations across experimental conditions, measured magnitudes are similar to those reported to place an operator at risk for occupation-related injury. Values observed for all conditions were greater than those reported by Marras *et al.* (1993, 1995). While pulling actions are generally linear in nature, a significant amount of rotation of the spine is necessary to create the load displacement. Part of the observed high levels of trunk rotation may be related to the experimental design, which did not allow the subjects to alter their foot positions. Perhaps if the subjects were allowed to step backward while initiating the pull, the amount of trunk rotation would be reduced. However, in confined workstations, the opportunity to manipulate foot orientations may not be possible. Allread *et al.* (1996) found that one-handed, unsupported lifts generated larger ranges of motion and velocities about the longitudinal axis compared to two-handed lifts. This is likely to be the case in pulling activities as well, notwithstanding any methodological restrictions placed on the subject.

The EMG profiles of the selected trunk muscles changed in a predictable manner given knowledge of the LMM data. From Table 8.3 and Figure 8.2 (a) it can be seen that as the operator moves away from the frontal plane containing the pull origin, the activity of both the left and right erector spinae increased significantly. A repeated measures t-test indicates that the right erector spinae is more active than the left ($p < 0.001$). %MVC values collected in this study are consistent with those reported for other submaximal, repetitive and occupationally typical experimental designs (Andersson *et al.*, 1996; Magnusson *et al.*, 1996). From a posture perspective, when the operator is close to the frontal plane, the back must assume a relatively erect posture. This limits the range of motion in the extension direction of the vertebrae and forces the erector spinae muscles into shortened lengths. Significant increases in erector spinae activity occurred as the reach distance increased. As the trunk flexes forward, the demands upon the erector spinae increase because of the increasing bending moments due to the head-arms-trunk segment. Furthermore, as the initial trunk position increases in the flexed position, the erector spinae muscles lengthen, likely placing them in more desirable lengths to produce the forces to contribute to trunk extension during the pull phase. Concomitantly, as reach distance increases, the spine is observed to increase its extension velocity and acceleration magnitudes in a statistically significant manner (refer to Table 8.4). Assuming that the erector spinae increased its rate of shortening in a similar manner to the spine kinematics, an increase in activity would also be expected (Hill, 1938). From a *post hoc* analysis perspective, there seems to be a clear differentiation in trunk extension function between the nearer and farther reaches lengths examined in this study.

Several authors have addressed the importance of the co-activity that occurs during various occupationally related movements (Marras and Mirka, 1993; Magnusson *et al.*, 1996; Marras *et al.*, 1998). Due to biomechanical modelling limitations, resolving the 3-dimensional forces and moments acting on the spine results in an indeterminate solution (Marras, 2000). An understanding of the relative importance of levels of co-activity can only improve the predictive capabilities of such models. Limited or reduced co-activation between the erector spinae and external obliques would be desirable during pulling activities as this would likely increase the net extensor moment created by the erector spinae, allowing for the operator to reduce the level of required force from the muscles for a given load condition (Lavender *et al.*, 1998). In all subjects and conditions, the erector spinae and the external obliques were co-active and the peak activities generally occurred near the beginning of the pull cycle. While not statistically different, the level of co-activation, as represented by the % MVC values, in the nearer positions seemed to be greater compared to the further reach conditions. Given that the trunk velocity and acceleration increase significantly with increased reach distance, it would be beneficial for this co-activation to decrease in order to decrease trunk stiffness during movement (Marras and Mirka, 1993).

While there is little consensus in the literature whether asymmetric postures elicit unbalanced co-activity from bilateral antagonist muscles (Gallagher *et al.*, 1994; Lavender *et al.*, 1998), the levels of asymmetry imposed in this experimental design (*i.e.* foot position, one-handed pull) required elements of co-activity across conditions. A repeated measures t-test indicated that there were no significant differences in the level of activity between the left and right external obliques. However, it should be noted that in some conditions the activity of the left external oblique was over 10% of its MVC value and in near pull conditions was functioning at a higher relative activity level than the erector spinae (see Table 8.3). van Dieen *et al.* (2000) suggest that an optimization-based biomechanical model to predict loads on the lumbar spine provides similar results, but with less required data acquisition, than an EMG-driven model for two-handed cart pulling activities. However, due to the observed levels of co-activity of the muscles about the trunk segment and the asymmetrical postures of one-handed pulling exertions, it is suggested that future kinetic analyses employ EMG activities in the prediction of spinal loading.

The EMG activity of the selected muscles around the shoulder complex behaved in an expected manner. This was concluded from a functional understanding of the primary actions of each and an insight into how the trunk musculature activity and spine kinematics changed due to increasing reach conditions. While the erector spinae increased in level of activity with increasing reach distances (see Figure 8.2(a)), the right trapezius and deltoid significantly deceased their levels of activity (see Figure 8.2(b)). Conversely, as the reach distance increased, the instance of maximum EMG activities of these muscles occurred later in the cycle (see Figure 8.3). When compared to the deltoid, the trapezius demonstrated greater inter-subject variability for when the maximum activity occurred within the pull cycle (see Figure 8.4). This is perhaps a reflection of the comparatively more complex muscle-tendon architecture which allows for a higher degree of freedom of recruitment through a greater range of shoulder joint motion. This might suggest that the distance the operator is positioned from the origin of pull imposes a varying load sharing or coordination strategy between the trunk and shoulder complex.

The decreased demands upon the shoulder complex, particularly the trapezius and deltoid muscles, for greater reach distances occurs because a trunk extension strategy is more efficient at exerting impulses upon the load earlier in the pull cycle. As discussed, when the operator is near the origin of pull, the spine is not in a suitable posture to contribute to the net impulse being applied to the load. Thus more demands should be placed upon the shoulder musculature in this situation. The moderate correlations between the times of maximum EMG activities of the trapezius and deltoid and time of maximum trunk extension velocity (see Figure 8.6) might also suggest an inverse relationship between how the shoulder and trunk segments make their contributions to a pull exertion as a function of reach distance. The considerable amount of variability in the time of maximum trunk extension is responsible for the lower correlation values in these results and reflects the differences in which individual subjects recruited the trunk segment to impose a change in momentum upon the load.

In general, the monitored shoulder complex musculature worked at a higher level of %MVC activity than the trunk musculature (see Table 8.3). Herberts *et al.* (1980) reported that sustained contractions at levels greater than 10% of a maximal voluntary effort could produce localised muscle fatigue. While the muscle activities elicited during this experimental protocol were during dynamic situations, observed activity levels for the trapezius and deltoid muscles from 22-73% MVC would likely lead to muscular fatigue under repetitive demands and would seem to exceed guidelines suggested for workloads acting on the shoulder complex (Vasseljen and Westgaard, 1997), particularly in the nearer reach conditions. The deltoid seemed to elicit the greatest relative activity of all the shoulder complex muscles monitored and would likely be at the greatest risk of all the muscles monitored for onset of fatigue. However, the level of deltoid EMG activity reduced at a more rapid pace as reach distance increased when compared to the rest of the monitored muscles. These data provide some support to the idea that neck and shoulder pain could well be the result of pulling activities (Hoozemans *et al.*, 1998). Laursen and Schibye (2000) found that loads on the shoulder muscles were very high, in cases where the loads on the low back were small. So it is not surprising that Hoozemans *et al.* (2000) found that shoulder complaints were significantly related to exposure to pulling (and pushing) while under the same conditions low back pain complaints were not.

While there was no significant experimental effect on EMG activities, both the biceps and latissimus dorsi seem to contribute consistently to the net motive pull forces across all the experimental conditions. Both these muscles also exhibited recruitment levels generally over 20%MVC and would seem to be important contributors to the net impulse applied to the load. Both these muscles have very diverse ranges of function and thus could be expected to adapt to various postures of the shoulder and scapula complex (Basmajian and de Luca, 1985).

When examining the trends in the spine kinematics and the directional changes of the activity patterns of those muscles that were significantly affected by changes in condition (refer to Figure 8.2 (a and b)), it seems that coordination strategies change as a subject moves further away from the plane containing the origin of pull. It appears that a shoulder strategy is employed for near pulls as limited erector spinae activity is observed, while the muscles surrounding the shoulder joint are very active. As the subject has to increase his reach a strategy related to trunk motion seems to predominate, thus reducing the relative activity of the muscles about the shoulder joint. This might provide some evidence that the subject is attempting to exploit the inertial properties of the trunk when the pull posture provides for that opportunity. While mechanical loading of the spine is of concern under these circumstances, it seems that the level of activity in the trunk musculature is of less concern than levels of activity observed in muscles surrounding the shoulder complex.

Caution must be employed when interpreting EMG signals from dynamic movements and relating these to segment kinematics. Muscle-tendon unit length-time histories were not considered in this study and changes in muscle activation may not necessarily reflect changes in muscle force production. However, the systematic changes (both increases and decreases) in the activation profiles for most of the muscles examined in this study suggest that muscle function, and likely load, changes with a change in pull reach distance. However, modelling muscle-tendon unit lengths during these pulling actions would be required to confirm the interpretations of these data.

There are a number of limitations to this study. In particular, the EMG analyses were limited to eight muscles and assessment of the trunk kinematics was estimated employing an exoskeleton device. Future studies should consider monitoring a larger selection of muscles and 3-dimensional segment kinematics should be collected. Only one point of origin and direction for the pull force vector was considered. While the effects of reach upon pull exertion performance was of primary interest in this study, results will likely differ as the origin of pull is relocated to less desirable positions. These data were collected under a reasonably controlled laboratory setting. Whether the experimental conditions reflect actual working conditions may be argued. However, in general, these results have provided a better understanding of agonist and antagonist muscle function and trunk kinematics for isoinertial, submaximal pulling activities.

8.5 Conclusions

With respect to the experimental hypothesis, as the subject increased the distance from the frontal plane containing the origin of pull the EMG activities of the erector spinae increased in magnitude. This reflects the greater flexion moments and increased range of motion the trunk experiences with greater forward reach. The EMG activities of the trapezius and deltoid muscles decreased with increasing reach. This suggests that the demands upon these muscles in exerting a pull force are greatest in pulls of close proximity to the operator. However, it should be noted that more specific kinematic and kinetic information is required to fully substantiate this interpretation. While there were considerable magnitudes of axial motion of the thoracolumbar segment in exerting these pull conditions, there was no significant effect by reach distance on motions in this plane. However, sagittal plane motions were affected by reach distance, as anticipated, and were found to increase in magnitude as the subject moved away from the frontal plane containing the origin of pull.

Based upon the data presented in this paper, several conclusions seem to be justified. Low-back overexertion injuries have been frequently associated with pulling activities (Andersson, 1997). While this is likely to be the case, given the large spine kinematic values during trunk extension and axial rotation, attention should be paid to the overall risk of shoulder injury in pulling motions. Data from this study suggests that the upper trapezius, mid-deltoid, latissimus dorsi and biceps brachii exert high levels of activity and in pulling postures similar to those used in this study would certainly be at risk for fatigue.

While researchers have reported on muscle recruitment profiles in relation to input requirements for EMG-driven force prediction models (Gallagher *et al.*, 1994; Lee *et al.*, 1989; Mientjies *et al.*, 1999), few have reported on the relative levels of activity of muscles recruited during pulling activities. In this respect, this research could provide a baseline for comparison of muscle recruitment levels measured *in situ.*

Much work must be done to understand better the strategies an operator will attempt to create a pull force under various postural conditions. If any strategy could be identified based on the experimental data, it might be that for closer pull locations (*i.e.* 10-20% stature from frontal plane containing the load) a shoulder strategy is employed, not necessarily because of mechanical efficiency but because the muscles controlling the spine are not in a desirable posture to create an extensor moment and contribute to a pull force. When the subject is at further pull locations (*i.e.* 30-40% stature from frontal plane containing the load) the subject seems to employ trunk extension strategies to assist in the pull exertion.

Data from this work suggests that subjects should exert pull forces at about 25% of stature from the frontal plane containing the origin of pull, particularly when foot movement is fixed or limited. At this distance, the load seems to be shared optimally between the trunk and shoulder complex and likely increases the time before onset of muscular fatigue. Attempting pull exertions at this reach distance will also allow the operator to exploit the inertial properties of the head-arms-trunk segment in generating load momentum.

Chapter 9

Summary and Conclusions

9.1 Introduction

Due to the complex interactions between technological, managerial, legislative and economic systems that govern all formal industries, quantifying the true health and economic impact of work-related injuries upon any economy is difficult. Those researchers who have attempted to estimate the fiscal liabilities due to work injuries have produced some staggering figures (Mital *et al.*, 1999). As reported in Mital *et al.* (1999), as of 1996 the National Safety Council in the United States estimated that total cost of injuries in the workplace to exceed $US 120 billion per annum. Furthermore, Ergonomists have a real need to promote appropriate accounting methods to determine the costs and benefits of ergonomic interventions, such as workstation redesigns. Whatever may be the true costs and whether these can be accurately accounted for (Negash and MacKinnon, 1998), most companies recognize that ergonomic programmes must become a pillar of the management paradigm and an important aspect of management's risk control strategies.

Economics aside, ergonomists are challenged with the task of reducing the incidence of work-related injuries by improving the work situation. However, establishing the efficacy of these programmes is difficult in light of the limited information regarding the mechanisms related to injury causation (Marras, 2000; Kumar, 2001). While the body of epidemiological evidence relating general heavy materials handling activities to overexertion injuries is increasing (Pope, 1998), much work is still required to isolate specific mechanisms associated with regionalized, anatomical disorders. Much is known about the bionegative effects of lifting, particularly of its association to low back injuries. However, comparatively little is known about how other materials handling activities, such as carrying, pushing and particularly pulling, impact upon the incidence of injury in the workplace (Hoozemans *et al.*, 2000). In this respect, measuring typical movement strategies or understanding the impact of poor workstation design should add to the body of information required to understand better the mechanical exposure upon the worker and provide an insight into the aetiology of work injuries (Westgaard and Winkel, 1996).

The purpose of this research was to gain a better understanding of how humans create pull exertions, characteristic of those tasks found in occupational settings. Before this issue could be considered, several methodological issues had to be addressed. Researchers have collected informative data under actual work conditions (Marras *et al.*, 1995; Norman *et al.*, 1998), but these time-series profiles represent a collection of mixed manual materials handling activities, predominantly those of lifting. While this information is clearly needed to assess occupational-specific risk for developing specific work-related injuries, a better understanding of pulling mechanics would best be undertaken when the movement is examined in isolation. The utility of laboratory-based versus worksite-based experimental protocols will always remain a controversial topic amongst ergonomists. However, there remains a great need to better understand whether operators employ discernible strategies to exert a pull effort and how specific workstation properties influence the execution of these strategies. In this respect, well-controlled experimental designs under laboratory conditions would be more desirable. A simplified experimental model that attempts to understand the components of a rather complex movement pattern is preferred as a first step to understanding broader issues such as the pathomechanics of injury or efficiency of movement.

Understanding the Influence of Pull Location on Maximal Performance

External loads are often used as foundation criteria to establish MMH design guidelines (Westgaard and Winkel, 1996). Much research has been done to assess the subject- and workstation-related factors that influence maximal levels of pull force production, generally under isometric or isokinetic modes of strength expression. Work described in Chapter 3 was one of the first research papers to systematically alter the absolute vertical and lateral locations of the origin of pull and to assess these efforts under varying postural conditions. The results demonstrated that for maximal isometric efforts, forces were maximised about pull locations near the anatomical sagittal plane and at about the subject's elbow height. This work reported one of the most comprehensive database on strength capacity of single-handed isometric pull exertions. These results were considered in the development of future experimental protocols in two ways: a) to select load magnitudes to employ in submaximal, repetitive activities and b) to consider the effects of the location of pull origins about a frontal plane upon dynamic exertions.

While the original intent of the study in Chapter 3 was to collect empirical data necessary to derive pulling guidelines, it was decided that to understand better how pull exertions are created then perhaps independent variables, such as load and pull location, used in future experimentation should be described relative to subject anthropometrics. The largest mean isometric pull force was 241N and this represented approximately 34% of the mean absolute subject mass. This load was thus considered to be the largest load that should be used in future protocols, particularly those exploring repetitive, submaximal dynamic exertions. Larger loads would not likely reflect those that would be manageable for prolonged periods of time, particularly if the location of the pull originated near the edges of the reach envelope. With respect to the pull heights, it seemed that the 1070 mm and 1610 mm seemed to impose practical differences in pull force values without being extremely different in magnitude (see Figure 9.1). These absolute pull height values were similar to the mean subject elbow (1092±26 mm) and eye (1607±58 mm) heights from the floor in a standing posture. The horizontal displacements of 0 and 200 mm were not significantly different. Therefore it was felt that some anatomical location within this horizontal displacement should be selected for use in future protocols and some anthropometrically-related distance no greater than 400 mm be selected as distances greater than this seemed to demonstrate no greater decrement in strength expression under isometric conditions.

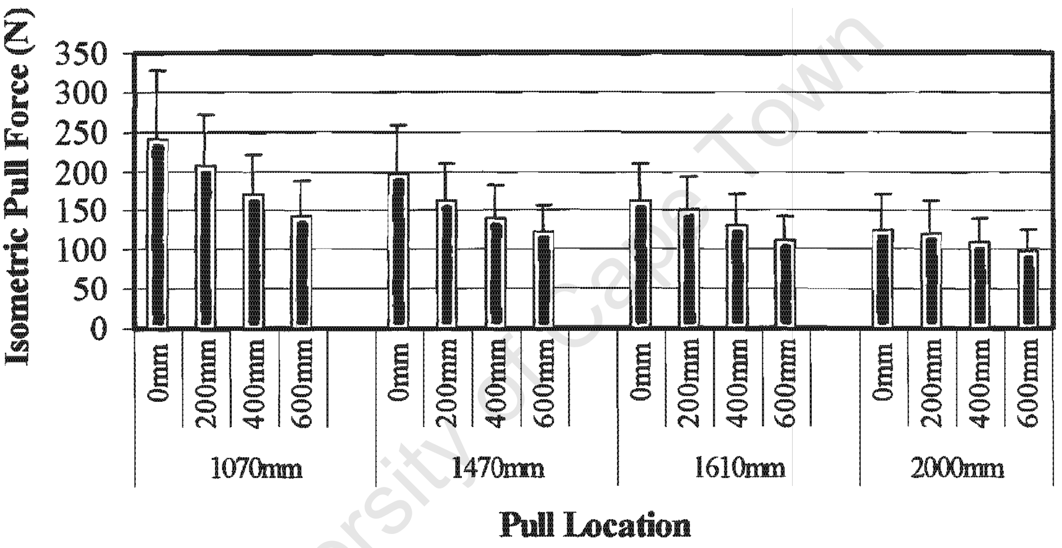


Figure 9.1: Mean (and standard deviation) isometric pull forces (N) for the free standing condition reported in Chapter 1.

Whether maximal isometric pull exertions are related to common *in situ* demands requires further exploration. This paper also highlighted the fact that postural constraints can significantly influence the magnitude of strength expression. Future studies on pulling should consider the extent to which posture is controlled during the execution of the pull force under laboratory conditions.

Acceptable Workloads for Repetitive Submaximal Pull Exertions

A psychophysical approach has been frequently employed to establish guidelines on acceptable limits for lifting (*e.g.* Mital, 1983; Ciriello *et al.*, 1990), although little has been reported for pulling activities. The data reported in Chapter 4 were assessed to determine whether a relationship existed between load and exertion frequency during simulated pulling activities. These exertions were executed under relatively optimal simulated workstation conditions and subjects were virtually free to execute the pull force in any desired manner.

Results from this study indicated that although the subjects were not trained operators in manual materials handling, their selected workloads were within physiological limits generally deemed acceptable for continuous work (Zhu and Zhang, 1990). Of importance was that the load~frequency relationship for loads greater than approximately 28% of the operators' absolute body mass produced high variability in inter-subject response. It has been suggested that tasks performed in a more biomechanically variable fashion will be more difficult to relate to tissue tolerance and mechanisms of operator injury (Granata *et al.*, 1999; Marras, 2000). Interestingly, Frings-Dresen *et al.* (2000) reported on mean and maximal pull forces observed *in situ* for the building and construction industries. Many pulling task forces were within limits described in this paper although many tasks, assumed to be repetitive in nature, well exceeded these absolute values. A limitation of the psychophysical approach to establishing guidelines is that these limits likely reflect accommodation of short-term responses to mechanical load and are not likely related to risk for developing injury. Therefore, guidelines derived using such an approach should be applied in a conservative manner and should be considered the upper limits within any design strategy.

Future examinations of submaximal, dynamic pulling activities must carefully consider what load values will be employed, particularly if the pulling frequency is high or the pull demands require less than desirable operator postures. These loads cannot be unrealistically low or high if the intention is discovery about movement strategies operators might draw upon to perform occupationally-related exertions. Results from this study suggest that loads greater than 25% of body mass (17.8±3.6 kg in absolute terms) might exceed acceptable limits of operators performing repetitive pull exertions under desirable workstation and postural conditions. As the posture becomes more awkward, or the workstation parameters become more constrained, these limits should be reduced considerably. These data seemed to be in reasonable agreement with those collected in Chapter 2. In the previous study, maximum loads were measured at a similar pull location as used in the study in Chapter 3 (*i.e.* elbow height and near the midline of the body). In Chapter 2 this maximal exertion was, on average, 24.6kg. This value is greater than the value deemed acceptable for regular handling in Chapter 3 (17.8±3.6kg). This might be expected as isometric forces should be greater than those created under concentric activations - all things being equal.

Another consideration emerging from this study was the potential advantages of using relative loads in future protocols. Some of the female subjects employed in this study could not adequately complete the conditions using higher loads. If the intent is to produce pulling guidelines then reporting empirical data in absolute values probably has greater utility to an Industrial Ergonomist. However, if the intention is to gain greater insight into movement strategies during pulling activities, then subjects should be compared against relative conditions. Furthermore, using relative values expressed as a percentage of lean body mass was also considered in future research protocols. A considerable amount of adipose tissue is located in the thorax region. For subjects possessing endomorphic characteristics, absolute loads might place such a subject at a disadvantage and require them to employ alternative strategies to produce changes in the momentum of the load, compared to mesomorphic subjects.

A more comprehensive study would have employed a number of diverse pull locations, such as those considered in Chapter 2. This is certainly recommended for researchers who might want to develop work guidelines for submaximal, repetitive single handed pull exertions using a psychophysical approach.

Experimental Control of Foot Orientation

While some researchers have promoted strictly controlled foot positions in pulling research (Warwick *et al.*, 1980), others have suggested that "free" foot positions are more closely related to realistic industrial events and have been associated with the production of higher force exertions (Grieve and Pheasant, 1981; Daams, 1993). Perhaps a compromise between these two methodological extremes is necessary in order to provide some element of experimental control yet not make the experimental results so esoteric that they cannot be properly applied in workstation design.

Chapter 5 examined how foot posture might affect the load kinematics during pulling activities. The first part of the Chapter reveals that there were individual preferences about how feet should be placed while executing a single-handed pull. However, certain dominant patterns emerged, such as when exerting a pull the contralateral foot is placed in a forward position, towards the frontal plane containing the origin of pull. This strategy increases the relative size of the base of support in the sagittal plane, thus increasing the overall system stability. Data from 50 subjects were used to establish average foot positions relative to the frontal and sagittal planes containing the origin and subsequent direction of the pull exertion. Fifteen newly recruited subjects were then employed in the second phase of the study to assess if the prescribed normative foot positions affected outcome load kinematics. Results suggested that while individuals might have foot position preferences for pulling exertions, placing them in prescribed positions did not significantly affect the load's velocity, force and power magnitudes during the execution of a submaximal pull effort.

In upright, standing pulling postures, foot positions will have an effect on the counter-moment acting against the moment due to the pull force vector. However, some element of experimental control with respect to foot position is necessary if comparisons of different pulling conditions are to be considered. In the experiments reported in Chapters 6 and 8 a lumbar motion monitor was employed to assess thoracolumbar kinematics. Motion of this segment of the spinal column is influenced by the function of the pelvic girdle. Pelvic orientation can change considerably with changes in lower segment orientation. If was deemed that if foot positions were controlled, then pelvic motion would be controlled better and thus changes in independent experimental variables could be more easily assessed. Since pelvic motion was not going to be measured directly it was felt that controlling foot positions was a reasonable methodological approach to consider for future experiments. Results from the study reported in Chapter 5 suggest that an element of control over foot positions can be considered reasonable for certain experimental designs. This statement may not necessarily hold true if the intent of the research is to compare pull exertions made about the extremes of the reach envelope when foot position adjustments may be necessary to maintain subject stability.

While there were some subjects who chose to place the right foot in front of the left in a right-handed pull, the predominant pulling strategy was to place the left foot in front of the right. In a left foot in front of right foot posture, the subsequent movement of the pelvis would put the upper body in a pre-rotated position. Table 6.2 in Chapter 6 reveals that the trunk was rotated to the left at the start of the pull exertion. This pre-rotation to the left was consistent across all experimental conditions and demonstrated statistically significant differences due to pull load and location (refer to Table 6.4 in Chapter 6). With respect to trunk muscle recruitment the right external oblique and the left erector spinae muscles demonstrated significant differences in activities and time to peak activities. Pope *et al.* (1987) reported that at the beginning of an isometric axial twisting effort the subjects rotated in a direction opposite to the direction of the motive twist. This tended to produce greater desired axial torques, less predicted load on the spine and more efficient muscle recruitment patterns in the oblique abdominal muscles. While it is unknown whether these results would be similar for dynamic axial rotations, or even for single-handed pulling exertions employing axial rotation to the right, identifying the left foot in front of right foot orientation as a superior posture for right-handed pulls seems intuitively to be correct.

When the results for the experiment in Chapter 5 were initially analysed and no load kinematic differences were observed, it was decided that this methodological issue was resolved. The main limitation to interpretation of these data is the fact that only one load and one pull location were considered and future research should expand upon this methodology to confirm that these prescribed foot positions continue not to produce significant changes in load kinematics for other pull conditions. Measures of subject kinematics, as well as load kinematics, should also be considered in future experimentation. While load kinematics remained unaffected between free and "fixed" postures, the subject may have chosen different postures in executing a movement strategy.

Kinesiological description of pull exertions under varying workstation demands

Introduction

Chapters 3 through 5 primarily address methodological issues important to the collection of laboratory-based pulling exertions. These investigations examined the effects of various workstation, load and subject postural factors upon the expression of pulling strength. Information from these studies was considered during the design of the experiments in Chapters 6 through 8. These studies examined subject responses to submaximal, repetitive and one-handed pull exertions against an isoinertial load.

Suitability of Experimental Pulling Loads

Classic experiments on muscle dynamics suggest that as rate of shortening decreases the capacity to produce force increases (Hill, 1938). Perhaps this was the impetus for early researchers attempting to derive guidelines to examine maximal pull force exertions under isometric muscle activations.

Figure 9.2 contains a graphical representation of horizontal pulling forces in the sagittal plane at approximately shoulder height. Three studies (Warwick *et al.*, 1980; Daams; 1993; MacKinnon, 1998) that were conducted under isometric conditions are compared to data collected under isokinetic conditions (Mital and Faard, 1990). The three isometric methodologies produced similar results but in comparison to more the dynamic conditions were almost 11 times smaller in magnitude. While isometric activations are thought to produce the greatest isolated *muscle forces*, when considering full-body, coordinated exertions, it becomes apparent that isometric models are not the appropriate approach to consider.

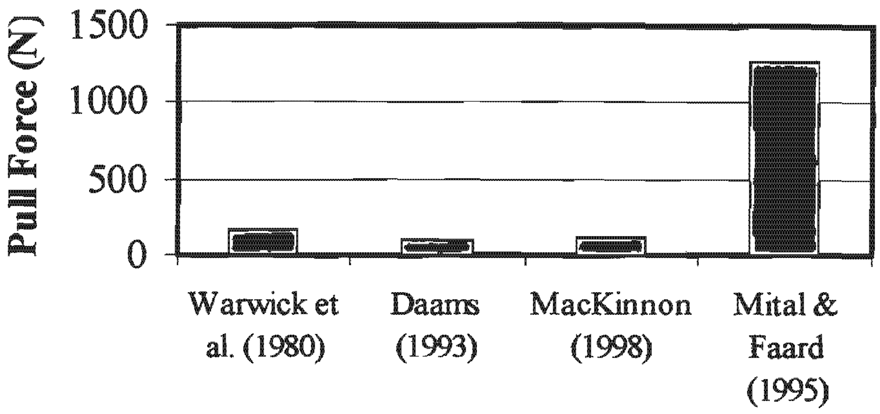


Figure 9.2: Comparison of the mean pull force (N) at approximately shoulder height in standing, feet-fixed postures. Data from Warwick *et al.* (1980), Daams (1993) and MacKinnon (1998) represent forces collected under isometric conditions, while Mital and Faard (1995) reflect pull exertions collected under isokinetic conditions.

The pulling exertions studied in Chapters 6 through 8 were performed under isoinertial conditions. These reflect better the demands upon operators *in situ* and certainly must be employed if a kinematic approach is used to examine pulling exertions. Loads of 6, 12 and 18% of lean body mass were selected as independent variables for the experiments in Chapters 6 and 7. These constitute loads that were well below the isometric and isoinertial loads evaluated in the first two experiments.

Future research could consider acceptable repetitive submaximal loads about various pull origins in the frontal plane. Neuromuscular fatigue, as assessed by signal composition methods, could be used to support how suitable submaximal loads remain as the pull origin locations move about workstation positions. Furthermore, representing data as relative values of isometric measures is not as meaningful given the changes in strength expression which occur under dynamic movement conditions.

Trunk Function During Pulling Exertions

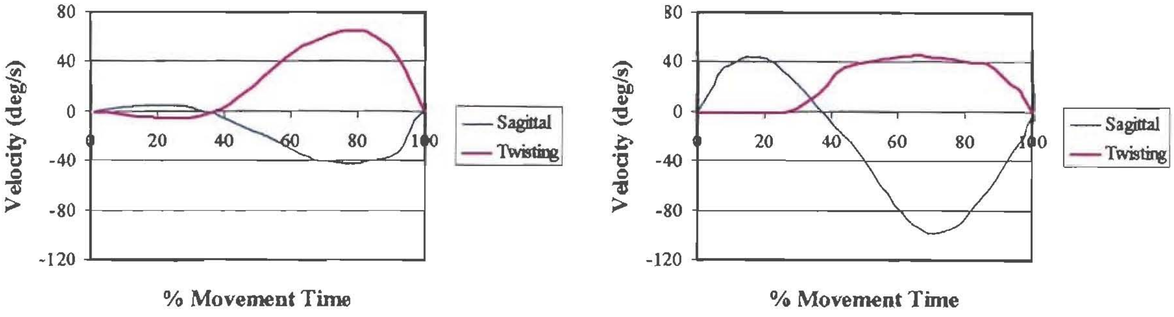
Considerable research has applied biomechanical models to estimate loads on the lumbar spine during various lifting conditions. While such prediction models have also been employed to examine loads during pulling exertions, there exists limited information detailing the kinematic and electromyographical profiles of the trunk region under varying pulling conditions that might be considered typical of work-related demands.

Researchers often underestimate the importance of biomechanical data for providing insight into human movement strategies and consequence of injury. One might assume that kinetic models are better predictors of work-related musculo-skeletal injury. However, Norman *et al.* (1998) found that kinematic variables and external loading factors were both independent factors in a model estimating relative risk for occupationally-related low back pain. They also correctly reminded readers that the degree of predictive ability of any kinetic model is largely related to the integrity of the input data, which tends to be based on kinematics.

During most pulling conditions, the subjects generated asymmetrical trunk extension velocities and accelerations similar to those observed in occupational settings for lifting tasks considered to be at risk for injury (Marras *et al.*, 1995). High velocities and accelerations during trunk extension and rotation will impose high loads on the spine (Marras and Wongsam, 1986) and decrease the stability of the operator. The spine extension kinematics, particularly the velocities and accelerations, tend to increase as load and reach demands increased. While axial rotations remains relatively similar across pull location conditions, they are of a magnitude for which risk of injury is identified as being high in comparable kinematics for occupations including lifting exertions (Marras *et al.*, 1995). Alterations to workstation designs and task demands which serve to reduce trunk segment motions about any axis will surely reduce the risk of injury to the lumbar spine.

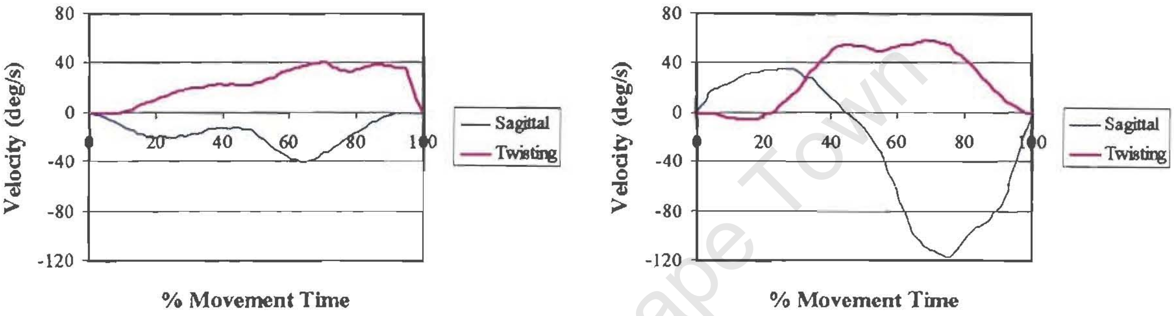
Figure 9.3 represents the sagittal and twisting plane angular velocities of a representative subject measured by a lumbar motion monitor for four comparable conditions. The kinematics were selected for the 10% reach, 40% reach, Elbow-In and Eye-Out conditions for the 12% lean body mass load from one subject who participated in all of the experiments reported in Chapters 6 through 8. These figures reflect how trunk motion can vary with change in pull task demand. In some cases the magnitudes of the velocities are significantly different but most interesting are the changes in temporal sequencing between the sagittal and twisting directions amongst different conditions. If one compares the 10% Reach and Elbow-In condition, the representative subject demonstrated opposite movement directions in the early stages of the exertion. In contrast, the lumbar motion monitor kinematics for the 40% Reach and Eye-Out conditions are remarkably similar. Further research is required to assess how workstation features impede an operator's choice of movement strategies, particularly those employed in trunk function.

With respect to trunk segment kinematics, further research to determine the existence of motor control strategies seems to be warranted. Perhaps like fundamental human movement patterns such as walking, throwing and catching, humans have "hard-wired" movement models upon which they draw upon to perform pulling exertions. If this is true then it is likely that humans draw upon these engrams to produce efficient pulling strategies.



10% Reach

40% Reach



Elbow-In

Eye-Out

Figure 9.3: Sagittal and twisting plane velocities from a representative subject over 4 related conditions.

Figure 9.4 integrates the temporal sequencing of peak load, lumbar motion monitor and trunk muscle EMG activities reported in Chapters 6 and 7. These data were originally collected concurrently. These data represent a clear picture of how neural activations precede segment motion. More importantly, load force appears to be at a maximum prior to maximum trunk segment motion. Maximum load velocity and power reach peak values after the peak forces. Perhaps identifying which segments have the greatest velocities in the horizontal directions at theses times will resolve what are the most influential segments contributing to the movement. The impulses necessary to meet load demands reflect combined contributions from the ground reactions between the floor and foot interface, the function of the arm and should complex musculature and the motions of the trunk. Future research must collect whole body kinematics to develop a comprehensible picture of segment interactions and sequencing and use these data to assess the kinetic interactions between segments (Putnam, 1991). Trend analysis of the time-records of various body segments and inter-segment correlations of these data could provide some insight into the important motion- and inertia-dependent terms of a pull task across varying workstation conditions.

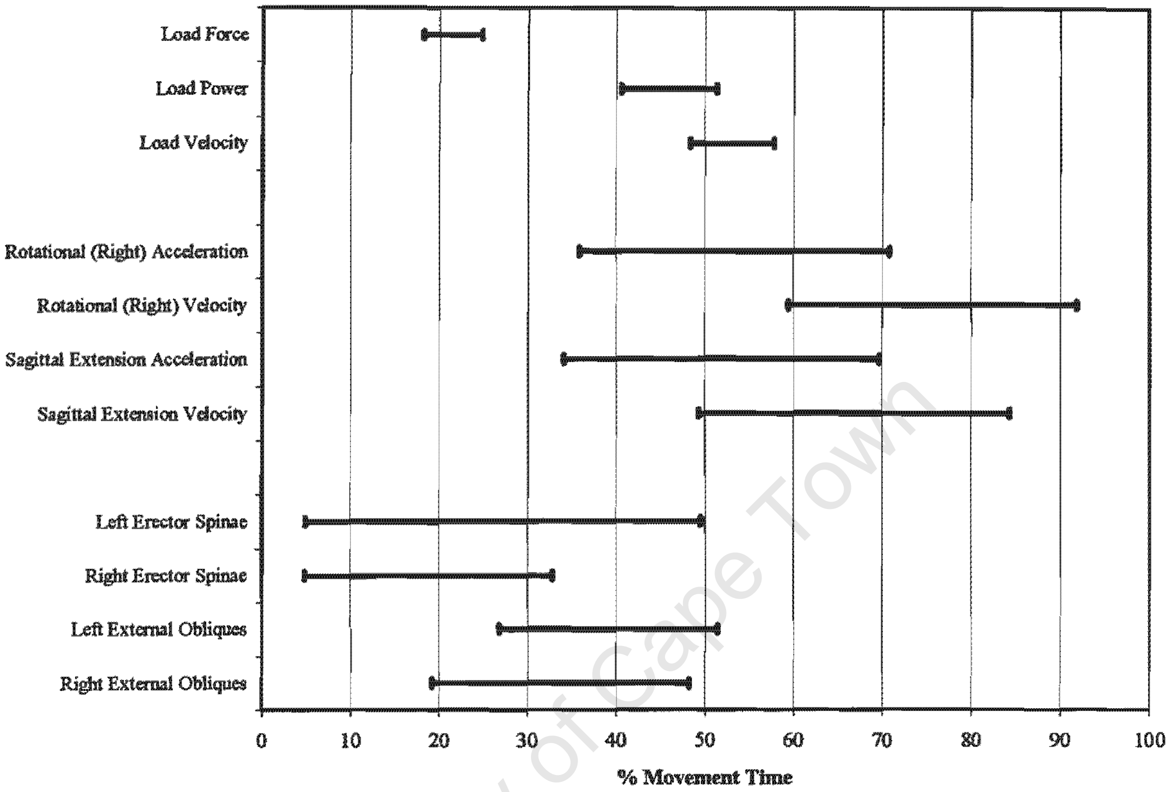


Figure 9.4: Variability, expressed as one standard deviation above and below the mean, of the time at which peak load, selected lumbar motion monitor kinematics and trunk EMG magnitudes occurred in the pull cycle (expressed as a percentage of movement time).

The evolutionary development of the spine is interesting from a form and function perspective. It is designed to protect the nervous tissue of the spinal chord and anchor rib structures necessary to protect and stabilize the internal viscera. The spine evolved to allow for bipedal locomotion. In order for upright locomotion to be efficient axial trunk rotation must occur and it has been suggested (Kumar, 2002) that rib structures at the lumbar spine level disappeared to allow for increased the mobility of the trunk. This development would contribute to more efficient gait by allowing contralateral asynchronicity of the upper limbs and furthermore, accommodate prehensile and forceful manipulative acts by the upper extremities. It is somewhat paradoxical that no trunk musculature had evolved with a suitable architecture to act as a primary agonist to create twist about the longitudinal axis of the trunk (McGill, 1991). Thus bilateral coordination of ventral and dorsal trunk musculature is necessary to initiate and control axial rotation and coordinate combinations of sagittal, frontal or horizontal plane motions. Ergonomists are continually researching the utility of optimization models to predict musculo-skeletal loading. Although these are relatively straightforward to implement, these models often fail to predict antagonistic muscle activity patterns, especially in tasks involving twisted trunk postures (Tan *et al.*, 1993; Thelen *et al.*, 1996). Interestingly, it is loads developed under these conditions that are often thought to be associated with low back overexertions. While researchers have employed EMG data to drive biomechanical prediction models, there has been limited description about the relative levels of activity of key muscles produced during pulling activities.

The data provided in Chapters 7 and 8 provide some benchmark EMG data which could help direct development of EMG- driven biomechanical models to assess the spine kinetics during single-handed pulling activities. The activities of these four trunk muscles can be considered reasonably similar even though the pulling exertions were performed at different speeds. As expected, the erector spinae were active during pulling activities, especially for the higher loads and more awkward pull postures. Cresswell et al. (1994) reported that back extensor activities as low as 25% of maximal voluntary activation are able to provide considerable joint stiffness in the trunk. In asymmetrical postures, particularly those with axial rotation, contralateral abdominal activations would be required to maintain this stability (van Dieen, 1996). What are most noticeable are the high levels of co-activities in the left and right external obliques during the pull movements, particularly in the more awkward pulling positions. These levels of co-activation would not only increase the stiffness of the trunk (Marras and Mirka, 1993) but would likely impose greater loads on the spine compared to instances when co-activity is minimised. Activity of the external obliques may also be necessary to decelerate the extending trunk during the later stages of the pull exertion in order to maintain stability over the fixed base of support. These results further emphasize the need to include all muscles activities when modelling spinal loads (van Dieen *et al.*, 2000).

The kinesiological data recorded from the trunk region indicates that trunk function is important for the exertion of a pull force. Given the diversity of conditions how an operator-produced exertion was examined, there seems to be an emergence of a coordination strategy with respect to motion of the trunk. This likely reflects part of an innate, comprehensive movement strategy, in which the subject exploits the inertial properties of large segments in order to create load momentum.

More importance has been placed on understanding the mechanisms of trunk control over the past decade. Continued research is required for a better understanding of the biomechanical cost-benefit of co-contraction and antagonist activity during axial trunk motions (Granata and

Marras, 2000). These types of activities can play two roles: create axial rotation or improve core stability. Understanding the relationship between these two functions, how these change with speed of movement, loading and variations trunk posture will improve our understanding of injury mechanisms and assist researchers in refining predictive biomechanical models.

Electromyographical Activities of Selected Shoulder Muscles During Pulling Exertions

Much ergonomics research has been devoted to understanding the effects of MMH practices on related injury to the spine. While a significant number of workers are reported to suffer from job-related back pain at a tremendous cost to the health care system and the general economy (Marras, 2000), musculo-skeletal injuries as a result of MMH occupations have been associated with other anatomical locations (Hoozemans *et al.*, 1998). Amell *et al.* (2000) suggested that awkward upper extremity positions are frequently observed in occupational settings and arise from poor workstation design. These poor working postures can generally be accommodated, in the short-term, by the operator because of the high degree of mobility about the shoulder joint. Often the problems associated with these poor postures are compounded with axial trunk rotation and excessive loads. Under repetitive exertions, the risk of injury would likely be high.

Hoozemans *et al.* (1998) suggested that musculoskeletal injuries other than those to the low back be given more attention. Soft tissue injuries to the upper extremities have been examined in the past (Waersted and Westgaard, 1991; Winkel and Westgaard, 1992) and these have generally been related to chronic submaximal loading patterns. Data from Chapters 7 and 8 indicate that the relative activations of the superficial muscles that control the shoulder joint are considerable during pulling activities. While pulling postures that require the subject to reach forward, higher or more laterally seem to affect significant changes in the trapezius and biceps muscle recruitments, all of the muscles of the shoulder complex were highly activated under each condition. This suggests that the internal loading of the shoulder is likely high, as is the risk for injury during pulling tasks.

Figure 9.5 provides a summary of the timing of peak EMG activities of selected shoulder musculature collected in the experiments reported in Chapters 7 and 8. In order to provide comparable information, only data from the 12% load conditions in the Chapter 7 experiment are compared with the data from the 20% Reach distance from the experiment reported in Chapter 8. Recruitment of this musculature seems to be relatively consistent between these selected, comparable trials, although the latissimus dorsi and biceps brachii appear to be recruited earlier, on average, in the 20% reach condition. As Imrhan and Ayoub (1990) reported, there may be distinct movement patterns consistent across pulling actions even though the workstation conditions change. Compared to Figure 9.4 the arm/shoulder musculature seems to reach peak activity before observed movement of the trunk, as measured by the lumbar motion monitor. The only exception might be the trapezius musculature. This suggests that coordination of the movements of the arm and trunk musculature must be important for increasing the momentum of the load during the early stages of the movement.

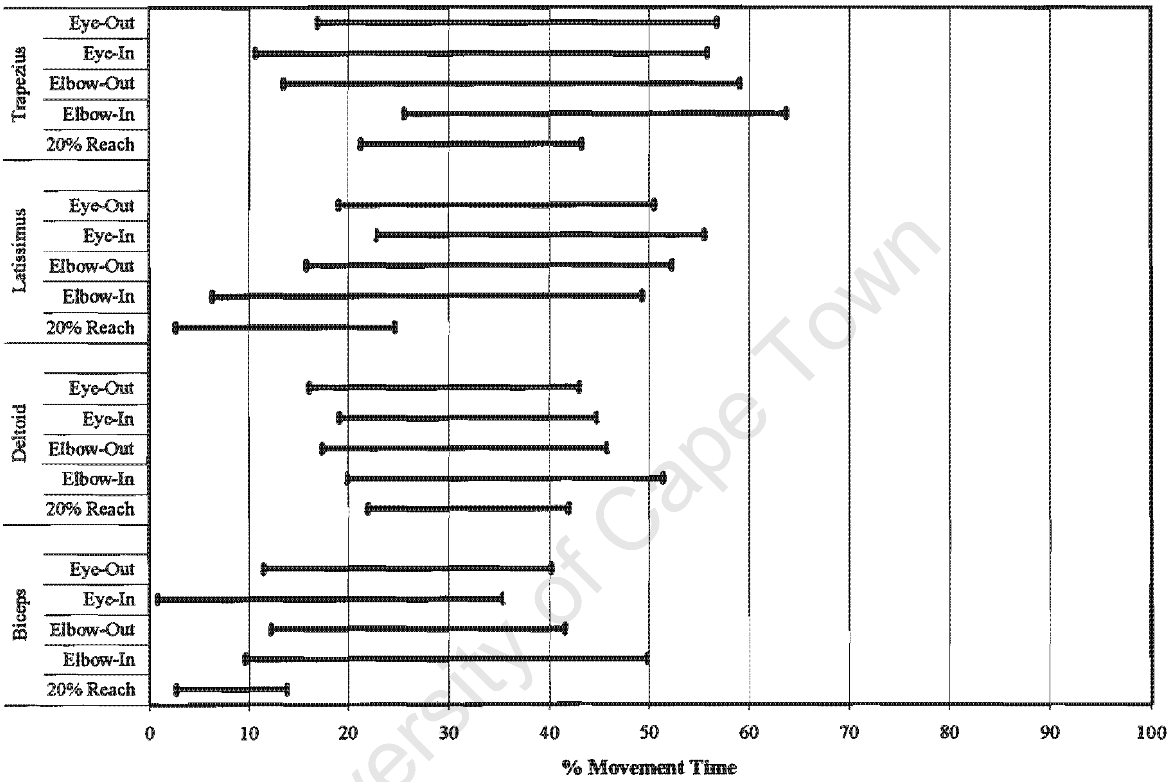


Figure 9.5: Variability, expressed as one standard deviation above and below the mean, of the time at which peak EMG magnitudes of muscles of the shoulder complex occurred in the pull cycle (expressed as a percentage of movement time).

Interpretations of the EMG profiles of these muscles are somewhat limited in the absence of simultaneously collected kinematic data describing motion at the shoulder joint. However, given the insight into trunk kinematics provided by these studies, it is likely that subjects rely on both trunk and shoulder musculature exertions in order to execute a pull force under various postural conditions.

9.2 Conclusions

These series of papers have contributed to a better understanding of the demands made upon and the strategies employed by operators who must exert single-handed pull forces in a horizontal direction. Future research should verify that task demands, workstation constraints and operator characteristics will all be independent and co-dependent factors affecting optimal work performances and potential for work-related injuries.

The demands of a task are influenced by the magnitude of the load, the rate of work handling the load and the location of the load relative to the operator. In order to minimise the internal loads upon involved anatomical structures requires minimization and optimization of the external loads being handled and includes the adoption of postures that suit both operator characteristics and workstation constraints. Even with current trends of automation or mechanization of heavy materials handling tasks, operators will continue to be exposed to undesirable human-machine interfaces, forcing less than desirable working postures.

With respect to load magnitude, it is clear that as loads increased above 6% lean body mass a scaling effect upon most of the measured kinematic and EMG variables was observed. More study is required regarding the optimal rate of work at which each of these loads could be handled in order to avoid any localised muscular fatigue.

Pull location does influence the response of those experimental variables and would likely influence the rate of fatigue at a given load. Minimising the height reached above elbow height and the lateral distance the sagittal plane within which the pull force vector is located from the glenohumural joint should minimise the biomechanical and physiological responses of the experimental variables. In terms of reaching towards a load in order to execute a pull force, there seems to be a load sharing strategy between the trunk and some of the shoulder musculature when the front foot is located approximately 20-25% of the subject's stature from the frontal plane containing the origin of the pull. While these findings are not necessarily definitive descriptions of ideal postures to assume while exerting pulling actions, they do provide a baseline for comparison of future work in this area.

Estimating the magnitude and loading histories of human structures are both technically and conceptually challenging. These challenges contribute to the uncertainties about the mechanisms of musculo-skeletal injury causation. From an epidemiological perspective, until the levels of internal loading are better understood, a clear understanding of the cause-effect relationship between manual materials handling tasks and operator injury will continue to elude Ergonomists.

This research has provided some direction towards optimizing the demands of pulling activities upon an operator. It is apparent that the operator will tend to employ both trunk and shoulder strategies in order to execute a pull exertion. In this respect, for less than desirable pulling postures, fatigue and/or overuse injuries would be expected to occur at the spine and shoulder joints. This research supports that a movement coordination, and thus, load sharing strategy likely exists between these structures and this relationship is highly influenced by the origin of the pull force vector. Furthermore, full-body kinematics and kinetic measures, such as joint forces and moments, are required to understand fully the relationship between the operator/surface interfaces.

Future kinetic models employed in research on pulling exertions will be required to accommodate asymmetrical loading of the body. To date, models utilized for lifting exertions generally consider two-handed exertions. While development of three-dimensional models have allowed researchers to consider twisting motions during lifting, they still employ simplifications of the human anatomy, particularly that of the spinal column. A better understanding of the form and function of articulations of the vertebrae and the shoulder remains critical model inputs for predicting joint loading during pulling activities.

9.3 Considerations for Future Research

Generating a pull exertion impulse against a load under less than desirable postures or workstation restrictions can be done by exploiting the inertial properties of the larger segments, such as the trunk. However the high EMG activity recorded for muscles about the shoulder joint suggest that this movement contributes significantly to the activity. While this research has contributed to the void in data regarding segment motions during pulling exertions, it has become apparent that co-ordination strategies employed to exert a pull force can only be adequately understood if the total kinetic link chain is examined. Although technologically challenging, full-body 3-dimensional kinematic measurements of both *in situ* and laboratory movements should be considered in future research designs.

Future researchers should devote more time and resources to measuring kinematic and kinetic time-histories of trained operators performing their manual materials handling tasks under actual occupational settings. One should never underestimate or disregard the effects of administrative controls, worker satisfaction and environmental factors, among many others, upon the performance of a skill. Measures obtained *in situ* can be correlated with injury reports and other pertinent epidemiological data. While this will not establish cause and effect between how an activity is performed and how injuries occur, this approach will serve to focus Ergonomists' attention on problematic pull conditions. While there are many practical problems associated with collecting data in occupational setting, not the least of which is how it might interfere with an operator's approach to executing a skill, these data will serve to refine how manual materials handling activities are simulated and explored under more controlled laboratory settings. The scientific method, from an ergonomics research perspective, will be more successful when a researcher has control over describing and manipulating experimental variables. The debate between occupational realism and laboratory control continues.

More attention should be given to deriving biomechanical models that predict forces and moments about the shoulder joint during pulling activities. There is little argument that the incidence of overexertion injuries to the shoulder complex will remain high until more is known about the manner in which this joint functions during repetitive pulling activities.

Measurement of the ground reaction forces acting upon a subject should also prove enlightening. Force plate measures could be integrated with the segment kinematics and measures of the external forces acting on the hand and employed in an inverse dynamics approach to estimate joint forces and moments. Centre of mass- or centre of pressure-time histories could also reveal if extreme pull origins move the path of these measures closer to the boundaries of the operator's base of support and thus, reduce the biomechanical stability of the system. This would certainly be useful for situations when the conditions of friction under foot are less than desirable or the operator is working on an unstable or compliant surface.

Future laboratory-based experimentation on pulling exertions should limit the number of methodological constraints placed upon a subject, thus increasing the freedom of how the operator produces a pull exertion at an upright workstation. Of primary interest is to allow the operator to move his or her feet during the execution of the pull force. There is some evidence that the strategies by which subjects with MMH experience moved their feet was somewhat different than novices when undertaking lifting activities (Delisle *et al.*, 1999). It would be interesting to establish if foot movement strategies reduce the levels of back extension or rotation or the high levels of EMG activities occurring in muscles surrounding the shoulder joint during common pulling exertions.

While the majority of research has focused on the back and the shoulder joints, the role of the lower limbs in free-standing pulling exertions should not be ignored. In order to exert a pull force, the operator must assume a reasonably stable position and generate the necessary counter-moment relative to the resistance of the load, avoiding slips or falls. Future research should examine the relationship between the foot-hand couple and whether changes in workstation demands affect the recruitment of lower limb musculature.

Future research should also determine if global coordination strategies occur in the execution of pull forces measured under a variety of work conditions. It is becoming clearer that experimental subjects created pull exertions using similar trunk motion strategies. This might provide support for the notion that pulling actions are a fundamental human movement and as such maintain very predictable motion characteristics even under diverse pull conditions. If so, identifying when these kinematic profiles diverge from normal ranges might provide some insights into conditions putting an operator at a higher risk for injury.

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