AN INVESTIGATION INTO THE BIOMECHANICAL CHARACTERISTICS AND PHYSIOLOGICAL COST OF THREE STANDARDIZED PULLING TASKS

GRANT HANDRIGAN

AN INVESTIGATION INTO THE BIOMECHANICAL CHARACTERISTICS AND PHYSIOLOGICAL COST OF THREE STANDARDIZED PULLING TASKS

By:

© Grant Handrigan

A thesis submitted to the School of Graduate

Studies in partial fulfillment of the requirements for

the degree of Masters of Science (Kinesiology)

School of Human Kinetics and Recreation,

Memorial University of Newfoundland

October, 2008

St. John's, Newfoundland

Abstract

The purpose of this study is to measure energy expenditure and trunk kinematics while performing three standardized pulling tasks. It is hypothesized that as the height of pulling increases (handle height) energy expenditure and trunk kinematics will change to reflect this. In order to accomplish this research twelve female and seventeen male subjects from a university aged population participated in the study. The subjects were instructed to pull at three heights (hip, shoulder, eye) at a rate of ten pulls per minute, for a period of 10 minutes (one hundred total pulls). The load was fixed at 15% of the subject's absolute body mass. Based on previous research, subjects were instructed to assume a standardized fixed foot position. This was performed in order to control the foot positioning while performing the pulling task. *Statistics:* The data set was verified to satisfy assumptions inherent with a repeated measures analysis of variance (ANOVA). Where main effects existed, a Bonferroni pairwise comparison was performed to determine significance. *Results:* Statistical significance was obtained for energy expenditure, sagittal displacement and twisting velocity. Hip pulling energy expenditure was lower than shoulder and eye pulling energy expenditure (7% and 11%, respectively, $p < 0.05$). Finally, twisting velocity at hip and shoulder pulling were 30% and 36% ($p < 0.05$) than twisting velocity at eye pulling. Hip pulling involves less sagittal displacement than shoulder ($p=.004$) and eye ($p=0.001$) by 37% and 46%, respectively. *Conclusion:* Physiological data indicate that all three heights of pulling are characterized as 'light' work and a slight increase in energy expenditure was apparent as the pulling height increased. This change in trunk kinematic movement strategies from a predominantly

twisting motion at hip height to a forward/backward flexion at eye height leads to an increase in energy expenditure in inexperienced individuals.

Acknowledgments

I would like to thank Dr. Fabien A. Basset for his tremendous support and unwavering faith in me throughout this entire process, it has been extremely formative and I am deeply grateful. I would also like to extend gratitude to Dr. Scott N. MacKinnon, Dr. Angela Loucks – Atkinson and other members of faculty and staff at the School of Human Kinetics and Recreation, Memorial University of Newfoundland.

On a more personal level I would like to thank my parents, always supportive and understanding, they assisted me throughout the process and I owe them everything. I would also like to thank my brother's, Christian, Gregory, John Paul and Joshua, each providing the necessary feedback and distractions when appropriate.

To my girlfriend Jaime, who has been tremendously supportive, understanding and encouraging, I love you and thank you.

For my friends Colin and Mark, thank you for the support, it was much appreciated and I hope that I can return it someday.

Finally, I would like to extend a sincere thank you to the twenty-nine individuals who were research participants in the present study.

List of Tables

List of Figures

List of Abbreviations

ANOVA – Analysis of Variance

CO_2 – Carbon Dioxide

$\dot{E}$ - Energy Expenditure

Hb - Hemoglobin

HR – Heart Rate

LBD – Low Back Disorder

Mb - Myoglobin

MMH – Manual materials handling

MSD – Musculoskeletal disorder

MSI – Musculoskeletal Injury

NIRS – Near –Infrared Spectropscopy

NTC – Negative Temperature Coefficient

O_2 – Oxygen

PAR-Q – Physical Activity Readiness Questionnaire

OHS – Occupational Health and Safety

RoM – Range of Motion

STPD – Standard Temperature Pressure Dry

SPSS – Statistical Package for Social Sciences

$\dot{V}_e$ – Pulmonary Ventilation

Chapter 1 – Introduction

1.0 Background of Study

Manual materials handling (MMH) is present in many industrial occupations; in its most simplistic form, it is described as the physical movement of inanimate objects. Several common examples of MMH are truck loading, lever pulling, and packaging. In industry, these tasks are often performed in a variety of environmental conditions and are often strenuous and repetitive in nature. Safety is a major concern in these occupations, a review of epidemiological research and risk factors suggests that pulling tasks put workers at an increased risk for injuries to the lower back and to the upper extremities (Boocock, Haslam, Lemon, & Thorpe, 2006; Frymoyer et al., 1980; Hoozemans, van der Beek, Frings-Dresen, van der Woude, & van Dijk, 2002; Hoozemans, van der Beek, Frings-Dresen, van Dijk, & van der Woude, 1998). Injuries to these common sites are thought to be preventable when the appropriate MMH strategies are in place. These MMH strategies are focused on reducing work load and incorporating automated assistive devices (de Looze et al., 2001; Hignett, Wilson, & Morris, 2005; Snook, 1978; Snook, Campanelli, & Hart, 1978). Injuries sustained on the job are a major source of lost revenue through increased workers compensation premiums, lost work time, equipment failure, and replacing and retraining staff (Dempsey, 1998). Injuries sustained on the job can also significantly affect worker's attitudes on the job, and in turn this will lead to a decrease in productivity and ultimately increases in risk exposure.

1.1 Purpose of Study

The increase in pulling actions in MMH(as opposed to lifting) (Koningsveld & van der Molen, 1997; Resnick & Chaffin, 1995) indicates the need to investigate appropriate heights for pulling. Investigating physiological and biomechanical variables can provide important information to identify risk factors for MMH. Energy expenditure (oxygen consumption) and trunk kinematics are important variables to quantify the physiological load and risk of injury. It is hypothesised that the level of pulling that requires the least amount of energy will be the most efficient pulling height. It is also hypothesized that there will be a change in trunk kinematics as the level of pulling increases. This prospective study attempts to provide additional information for future investigators to determine (and reduce) risk factors for musculoskeletal disorders caused by repetitive strain injuries from MMH tasks, specifically pulling. This study will not directly measure musculoskeletal disorders or injuries; rather, it will measure energy expenditure and trunk kinematics as predictors of musculoskeletal injuries.

1.2 Significance of Study

In this prospective study we are attempting to examine the efficiency of pulling tasks. The majority of literature on manual materials handling (MMH) is focused on lifting mechanics of the lower back and upper extremities, there is significantly less reported on pulling and manual materials handling (Garg & Beller, 1990; Hoozemans et al., 1998; Kelsey, Golden, & Mundt, 1990). Despite the narrow focus of the research, little has oriented around the energy cost of performing such tasks. As noted by Dempsey (1998), there is a lack of quantitative research investigating the possible link between risk factors and potential for injury of MMH tasks. This prospective study will attempt to archive the energy costs of performing a standardized repetitive submaximal pulling task in a simulated industrial setting. The methodology is selected to reflect previous designs, further investigate possible scenarios and it is an attempt to simulate an industrial task. Automation in industry has increased the use of pulling tasks; in order to reduce injury risk, it is necessary to investigate these tasks and find an 'optimal' level of pulling. Information to identify musculoskeletal injury risk factors for manual materials handling will also be reported.

Chapter 2 – Review of Literature

2.0 Introduction

Current trends in manual materials handling (MMH) indicate that there is a shift in the characteristics of many occupations. Occupational tasks are becoming increasingly automated and facilitated through ergonomic interventions (in order to increase efficiency and reduce occupational risk to workers), as a result, there are many changes, notably from lifting tasks to that of pulling tasks (Kelsey et al., 1990; Koningsveld & van der Molen, 1997; Snook, 1988). Current estimates indicate that nearly half of all manual materials handling tasks involve some form of pushing or pulling (Baril-Gingras, 1995; Hoozemans, van der Beek, Frings-Dresen, van Dijk, & van der Woude, 1998). The replacement of many lifting tasks with a pulling task has brought about several changes in industrial settings, most importantly; advantageous and disadvantageous changes in exposure for the worker. It is possible that the shift from lifting to pulling tasks will result in a reduction in musculoskeletal injuries if there is a corresponding reduction in exertion (demand placed on the system). This would come as a result of the automation of manual materials handling in industry. It is important to stress that when using mechanical aids it is necessary to appropriately design them so as to not cause any further stress or strain; these aids are meant to reduce the workload. At the present time these are speculative and mostly unfounded claims, whether there will be an overall reduction in musculoskeletal disorders or a change in injury type remains to be demonstrated and will most likely be described through epidemiological studies investigating these changes (occupational risk factors).

There exists a significant amount of research literature available on manual materials handling (MMH), this research is primarily focused on MMH and the musculoskeletal disorders associated with lifting. A smaller portion of this research focuses on pulling (and/or pushing) tasks. This research attempts to accurately determine causative factors for musculoskeletal injuries related to pulling and concludes that it is necessary to investigate the many risk factors that might lead to an injury. These risk factors are often evaluated and investigated from three common perspectives: psychophysical, physiological and biomechanical, a fourth perspective also available to observe risk factors from large groups is epidemiological studies (Hoozemans et al., 1998). To summarize the focus of this review of literature, we will investigate the risk factors of two perspectives; biomechanical and physiological, and more specifically their characteristics into two major categories; operator-related factors and task-related factors.

In the literature there exists three methods to separate and describe the risk factors for manual materials handling, these methods are as follows. The first method was used by Hoozeman *et al.* (1998) and is described in their excellent review on the risk factors for pushing and pulling tasks. It was based on the models proposed by Westgaard and Winkel (1996) and Van Dijk *et al.* (1996) and involves describing the risk factors in terms of these three principle characteristics: a) *work situation* such as distance, frequency, handle height, and cart weight b) *working method* such as posture, movement, exerted forces, foot distance and velocity and c) *worker's characteristics*, such as body weight, and work capacity. The second method of describing the risk factors was proposed by Winkel and Mathiassen (1994) and describes each task as having three main dimensions that are important for consideration, the intensity (amplitude and direction), frequency, and duration. A third and final approach to describe the risk factors of a manual materials handling task is to separate the task into operator-related factors and task-related factors. As we are examining a specific task, this is the approach that we will use in our review of literature to investigate pulling tasks.

A common thread between all methods of describing the risk factors is that it must focus on the risk factors and characteristics that overtax the musculoskeletal system in order to be able to effectively reduce the demand. In addition, to understand the cause(s) of injuries from a pulling task it is necessary to quantify the exposure to work into meaningful data and draw logical conclusions that will reduce musculoskeletal injuries (Hoozemans et al., 1998; Waters et al., 1993).

A pulling action is defined as a hand action that has a resultant force vector that is parallel to the ground (Baril-Gingras, 1995; Martin, 1972). To avoid confusion it is necessary to describe the details of the task, such as if the object is fixed (static) or moveable (dynamic) as there is a considerable difference in the muscular contractions and resulting physiological effects of performing these actions. Earlier focus was on the static performance of a task, however, recent research in this area has focused on the dynamic performance of pulling tasks. We are also examining a pulling task that is typical of fixed workstation activities, in that the lower body is in a relatively stable position and the upper body performs dynamic activities to displace the object. Finally, pulling can be regarded as either a one handed (asymmetrical) or a two handed (symmetrical) pulling task. To summarize our interests in pulling tasks, when possible, we will focus on the upright, sub maximal performance of a one handed (asymmetrical) dynamic pulling task from each of the following approximate participant heights: hip, shoulder and eye level.

2.1 Physiological

The performance of any physical activity which requires the use of a large muscle mass, during static or dynamic contractions will result in acute changes to the cardiovascular, pulmonary and musculoskeletal systems. In order to quantify the work performed, or measure the 'cost' of performing the physical activity it is necessary to measure the *In Vivo* biochemical changes. Metabolism represents the total sum of all biochemical processes occurring in a living organism, and in this case a physically active organism. There are two methods to measure metabolism, direct and indirect calorimetry. The first method, direct calorimetry is based on the principle that heat is a byproduct of metabolic processes. The measurements of these processes are based on quantifying the total change in energy (heat) in a closed system. Direct calorimetry is not practical as a measure of energy expenditure in a working environment because of the difficulties associated with working in a closed system, that is, most mechanical equipment will produce heat energy when functioning. The second method (i.e. indirect calorimetry) measures total gas exchange (O_2 and CO_2) by the body. It is dependent on the most common way of extracting chemical energy from a substrate, to completely oxidize it to carbon dioxide and water (Ferrannini, 1988). This is the most common method of measuring metabolic changes.

To understand the basis of indirect calorimetry as a measure of energy expenditure it is necessary to distinguish between the actual measures of this technique and what is estimated or assumed. Indirect calorimetry measures oxygen consumption and carbon dioxide production. These measures are then used to estimate the energy production of the system (often incorrectly called energy expenditure, although through conventional use energy expenditure appears to be the more 'correct' term). In a steady state these are equal and perhaps this is where some of the confusion stems from. As well, this measure is dependent on the accuracy of the oxidative reactions of the common fuels (carbohydrates, lipids and proteins), that is, if for some reason there is a departure from the standard stochiometric equations the accuracy of these estimates are therefore put in question. A common example of this departure is if the sources of carbohydrates are blood glucose or muscle glycogen. Despite these considerations it is well accepted that metabolism is highly dependent on oxidative energy pathways, as a result, measuring gas exchange is a good predictor of metabolic rate (Brooks, 2004). With respect to determining energy production rates in physically active individuals through the use of indirect calorimetry it is necessary to capture the changes in metabolic rate brought about by an increase in working demands on the body. The primary changes are increases in pulmonary ventilation ($\dot{V}e$– responsible for supplying oxygen into the pulmonary system) and increases in heart rate (HR – responsible for supplying oxygenated blood to the working muscles). These two variables are typically reported to quantify the changes in workload (Hoozemans et al., 1998); indirect calorimetry (oxygen consumption) is becoming more commonly utilized as a measure of change in workload (Li, Yu, & Han, 2007). Quantifying the physical workload is important for measuring the demand to ensure that it does not overtax the system. In this section of the review of literature we will investigate both the operator-related and task-related physiological factors for a pulling task.

2.1.1 Operator – Related Factors

Sexr

The sole operator related factor that is considered when performing ergonomic assessments of occupational tasks is sex. Generally speaking, sex differences exist when examining working capabilities. These differences exist as basic physical and anthropometrical differences between sexes, including differences in strength and aerobic capacity. Miller *et al.* (1993) found that females exhibited lower voluntary strength in both upper (52%) and lower body (66%) measurements when compared to male counterparts. They reason that the reduction in upper body strength is a result of females having proportionately less of their lean body mass in the upper extremities and that overall, the data from their research suggests that the greater strength of males is primarily due to their larger muscle fibers (Miller, MacDougall, Tarnopolsky, & Sale, 1993). Females also have a lower reported aerobic capacity than males. Data reported from the American College of Sports Medicine's guidelines for exercise testing and prescription (2000) indicate that females have values approximately 5% to 15% lower than males. These lower values are reported as a result of differences in blood volume, hemoglobin and cardiac output. Charkoudian and Joyner (2004) report that even when females and males are matched for size they have a lower blood volumes, and correspondingly lower hematocrit values, both leading to reduced oxygen carrying capacity. They also report that the greatest difference between sexes with regard to cardiac output (cardiac output is the product of stroke volume and heart rate) during exercise is that females have lower resting stroke volumes. The combination of these lower values (blood volume, hematocrit and cardiac output) result in an overall lower aerobic capacity for females. These established differences can affect how women perform manual materials handling tasks. As females have an overall lower muscle mass (strength) and aerobic capacity than males, they may exhibit greater perceived (psychophysical) and actual (physiological) energy expenditure while performing the same task. Several studies have investigated these sex differences with respect to task performance and have adopted recommendations based on their findings. Generally when dealing with the sex differences, tasks are modified accordingly to the differences in the sexes. For example, if a task requires a significant amount of strength, the task will ideally be matched with an individual capable of completing the task, or an assistive device will be provided to ensure a safe working environment. This is a general principle for ergonomics and workplace design, these 'special' arrangements are made to accommodate the operators capabilities, regardless of sex or anthropometric differences.

A study performed by Nijenhuis and Roseboom (1987) investigating the impact of sex on energy expenditure and heart rate concluded that males had higher energy expenditure and that females had higher heart rates while performing similar tasks. As already mentioned, investigations on the physiological exposure of manual materials tasks are limited, and there exists considerably less sex based investigations. This fact is important to consider when designing occupational tasks. Designing workload adjustable workstations is a method to overcome this limitation.

Van Der Beek, Kluvers, Frings-Dresen, and Hoozemans (2000) performed a study investigating sex differences in exerted forces and physiological load during pushing and pulling of wheeled cages by postal workers. Eight female and four male workers handled four-wheeled cages under eight conditions corresponding to the cage weight (130, 250, 400 and 550kg) and the direction of force exertion (pushing or pulling). The physiological variables that were measured included heart rate and oxygen uptake. Analyses without correction for anthropometric factors revealed significant sex differences for oxygen consumption and heart rate. This difference was not observed when corrected for anthropometric factors (body weight, height and maximum capacity). These authors concluded that the differences were not due to push-pull strength or physiological capacity but to other strategies, possibly pacing strategies. They concluded with recommendations to systematically analyze differences in task performance with respect to sex in future studies.

In a recent study performed by Maikala and Bhambhani (2007) they investigated eleven (11) male and eleven (11) female subjects for peripheral circulatory responses *In Vivo* via near infrared spectroscopy (NIRS) during an incremental pulling and pushing task to exhaustion. They concluded that pulmonary oxygen uptake during pushing and pulling was influenced by sex, the NIRS-determined oxygenation and blood volume responses suggest that in both the biceps and the lumbar muscles at their peak workloads, oxygen delivery and utilization were similar in both sexes. They suggest that future studies of occupational task assessments investigating O2 uptake kinetics should measure pulmonary O2 uptake and peripheral circulatory responses in both men and women to measure efficiency. NIRS is a relatively new technique that measures muscle energetics and has applications in many fields. It is a non-invasive optical technology used to estimate tissue oxygenation by applying the physical principles associated with light absorption and scattering in the muscle. NIRS is based on the light absorping and differential properties of oxygenated and deoxygenated hemoglobin (Hb) and myoglobin (Mb) in the muscle tissue. In the near infrared light range of 700-1000nm, the absorbed light by oxygenated Hb and Mb (Hb/Mb-02) and deoxygenated Hb and Mb (Hb/Mb-H+) display distinct absorption spectra. By measuring the resultant difference in their respective spectra, we can obtain a representation of the relative change in tissue oxygenation (Ferrari, Mottola, & Quaresima, 2004; Neary & Bhambhani, 2004). Despite the apparent benefits of such a measurement technique there exist two main applicable limitations to this method; i) the potential interference of tissue thickness (adipose, muscle, and bone), and ii) the inability of the NIRS signal to discern between Hb and Mb muscle content because of their overlap in the NIRS range (Ferrari et al., 2004). The main attraction with this technique is its low cost and non-invasive technique to measure specific muscle oxygen consumption. Because of this it is increasingly becoming a more reliable and valid measure of muscle energetics. This is useful for identifying specific muscle actions and energetics during the performance of a task.

These investigations suggest that a sex difference does exist in physiological responses to MMH and that future investigations and job modifications should include this information when designing research investigations and job modifications.

2.1.2 Task – Related Factors

Load

A considerable amount of research has investigated the effects of the load of the object that is to be pushed or pulled and the physiological implications for the worker

(Hoozemans et al., 1998). Several studies (Datta, Chatterjee, & Roy, 1978, 1983; van der Beek & Frings-Dresen, 1995) have found an increase in energy expenditure ($\dot{E}$), pulmonary ventilation ($\dot{V}_e$), and heart rate (HR) with a concurrent increase in the load of the object that is pushed or pulled.

Datta, Chatterjee and Roy (1983) investigated energy expenditures and heart rates under different operational conditions for pulling handcarts. The investigators measured the effects of pulling handcarts which varied in weight (190kg, 375kg, and 560kg). The participants walked at 5 km • h^{-1} for ten (10) minutes and expired air was collected in a Douglas bag and measured during the ninth (9^{th}) and tenth (10^{th}) minute. As expected with increasing loads, the pulmonary ventilation, energy expenditure and peak heart rate values increased proportionately. The authors concluded that the pulling handcart was efficient at performing this difficult task.

Van der Beek and Frings-Dresen (1995) investigated lorry drivers over a full day period. They recorded heart rate throughout the entire work day and found that in general, the highest HR was found during loading and unloading. As part of the experiment they performed a work simulation in the laboratory and found that the lorry drivers worked at anywhere from 35%-50% of their $\dot{V}O_{2max}$ for the hardest tasks, which were loading and unloading, particularly those involving pushing and pulling tasks. For this occupation the authors suggest that pushing and pulling tasks create the greatest demands. It is reasonable to suggest that tasks that require the largest amount of energy expenditure can also lead to the greatest level of whole-body and localized fatigue amongst the workers and potentially lead to increased musculoskeletal injuries.

Unless the study is investigating the effects of increased load on physiological variables, the load is usually fixed and constant throughout the experimental protocol. Several different methods have been used to select the appropriate mass for pulling, such as: percentage of absolute body mass (MacKinnon, 2002), or a specific occupational task is being investigated such as the pushing or pulling of mail carts (Hoozemans et al., 2002). Overall, there does not seem to be a standard load determined, it varies widely with each experimental design.

Handle Height

The majority of research investigating handle height and manual materials handling has investigated a wide range of heights. A general sort of consensus seems to have emerged and the majority of task range between one meter (from the floor) and shoulder height (Hoozemans et al., 1998).

Ciriello and Snook (1983) investigated varying handle heights and the physiological demands of performing a pulling and pushing task. The task consisted of pulling a large box a distance of 2.1m at three selected levels (height) of pulling. They describe the levels of pulling as being high (shoulder height), mid (distance midway between knuckle height to elbow height) and low (15cm below knuckle height). They investigated the cost of two handed pulling and pushing for each of these heights. These authors concluded that there was no significant difference between heart rate and the three levels of pulling.

When investigating the effects of handle height on physiological measurements it is important to note that many of the investigations on handle height use a variety of different protocols and heights. Some use a specific height to simulate an industrial task;

others use it as a general approach to examining the effects of different handle heights on pushing and pulling (Chaffin, Andres, & Garg, 1983).

2.1.3 Physiological Future Directions

There is a considerable need for a greater number of studies on the physiological demands of pushing and pulling tasks. Many of the current studies have significant limitations, such as a small sample size, lack of field tests, and a lack of methodological standardization between research investigations. The majority of the research investigations use the psychophysical approach to measuring working capacity. This is a problem as several investigators have concluded that psychophysical ratings have often over selected work exertion levels. This would allow for a greater understanding of the demands placed on the workers in their respective occupational settings, this could lead to job/task specific reductions in musculoskeletal injuries. There is a need to investigate pulling and pushing tasks in both a holistic and a systematic manner as each perspective offers something of importance to the overall understanding of risk factors for musculoskeletal injuries from pushing and pulling (Dempsey, 1998).

2.1.4 Summary

In summary, when investigating physiological research there are few studies that have focused on the effects of different pushing and pulling tasks on internal exposure, these studies often use different protocols and measure different variables. Therefore it is too early to offer any serious recommendations that are soundly researched and concluded. The influence of sex, load, and handle height on pulling tasks and the resultant physiological strain have occasionally been studied, even rarer are investigations on pulling frequency and its effect on the physiological strain associated with a pulling task. Their remains many gaps in our understanding of the relationship between pushing and pulling, risk factors and muscle fatigue. (Hoozemans et al., 1998) At this time, there is not enough evidence to say that an increased physiological demand results in an increased risk for musculoskeletal injuries.

2.2 Biomechanical

The musculoskeletal system is a complex system of interactions between muscles, joints, tendons and ligaments. The use of potentiometers, accelerometers, and kinematic measurement systems to determine the displacements, and then subsequently calculating the velocities and accelerations of the movements allow for an in depth analysis and understanding of the kinematics associated with the body's movements. In order to measure the trunk kinematics while performing a task, there is a need to have valid and reliable collection techniques.

In the context of this review of literature, a pulling action is defined as a hand action that has a resultant force vector that is parallel to the ground (Baril-Gingras, 1995). There are many factors to consider when investigating the biomechanical components of a pulling task; these are posture, foot position (stance), load, pulling frequency, handle height, and sex. Once again, the characteristics will be separated into operator-related effects and task-related effects.

When investigating the biomechanical performance of a pulling task there are several general and important characteristics that must be controlled. For example, pulling tasks can require individual body segment movements or whole-body movements as well as different types of muscular contractions. For example, when investigating the biomechanical factors it is necessary to consider whether the investigators are looking at an isolated individual body segment or if it is a full body approach to performing the task. This is relevant because if we are investigating an individual body segment we must consider if the experiment has sufficiently isolated the body segment and if we can objectively observe one individual segment, thereby allowing a proper isolation of the area as a potential site for increased risk of musculoskeletal injuries. If we are observing a full body approach to the research it is less effective at finding specific injury sites for different occupational tasks but sometimes necessary when performing whole-body or functional movements.

It is also necessary to consider the muscular contraction of the pulling task, for example if the object is to be displaced or if it is fixed. An object that is displaced will require a dynamic muscle action (eccentric, concentric, or both), whereas a fixed object would require a static muscle action (isometric). As well as the different muscular contractions possible (isometric vs. concentric/eccentric) whether the object is moveable or stationary greatly affects the biomechanical performance of the task. A fixed object would involve considerably less movement of the body and its body segments, whereas a moveable object would most likely involve the whole body movement and the coordination of several body segments, resulting in an increased risk of injury to several different locations for the performance of one task.

2.2.1. Operator – Related Factors

Sex

Different male and female anthropometric characteristics can affect the biomechanical nature of pulling tasks. Investigations into force production and gender have revealed that females generally have smaller musculature and are therefore not as strong as males, for many of the same tasks females would need to expend more energy to produce the same force output (Cheng & Lee, 2004). These authors investigated twenty-nine (29) Taiwanese men and thirty-one (31) Taiwanese females on one-handed and two-handed pulling tasks over a variety of heights (48cm, 84cm, 120cm, and 156cm).

They concluded that for similar tasks the females pulling strength varied from fifty-nine to sixty-seven percent (59%-67%) of the males' strength. The authors also made allowances for subject anthropometrics and still concluded that significant differences existed between sexes. To achieve similar force outputs (in order to perform the same action) females may require more muscular recruitment or the use of additional body segments, both of which may alter the biomechanical performance of the task.

In a more recent publication that investigated sex differences in exerted forces and physiological load during pushing and pulling of wheeled cages by postal workers these authors hinted that a difference in the biomechanical performance of tasks occurred between sexes. They suggested that despite all subjects having fifteen (15) seconds to perform the push/pull task, men and women adopted slightly different working methods. They reason these suggestions based on females taking longer time to perform the task (van der Beek, Kluver, Frings-Dresen, & Hoozemans, 2000) and concluded that future research in this area should investigate to see if different working methods or strategies are utilized based on sex comparisons in order to accomplish the task.

2.2.2. Task – Related Factors

Posture and Handle Height

A working posture is defined in several different ways, the biomechanical alignment, the spatial arrangement of body parts, the relative position between body segments, and the body attitude assumed to perform the tasks (Vieira, 2004). Posture has been observed to have a significant effect on the performance of a pulling task (Chaffin et al., 1983). After reviewing the literature on posture, these authors reasoned that it is important to control for posture and that it is dependent upon several factors such as height, task instructions and floor friction. With three (3) male and three (3) female participants they set out to expand on previous research conducted by Ayoub and MacDaniel (1974) and one of their research objectives was to measure how posture is affected by handle height. They controlled the following variables: posture instructions for two foot placement strategies (feet symmetrically placed beside each other and with one foot in front of the other), handle height (68cm, 109cm, and 152cm), one-handed or two-handed, and push/pull force directions. These authors concluded that handle height significantly affected posture and that future biomechanical models, and research investigations of push and pull strengths and/or workplace layouts should consider posture as much as the other common workplace design characteristics when designing work stations and working tasks.

In a more recent study by Resnick and Chaffin (1995) they argue that individuals rarely perform tasks in one single plane, movements often encompass multiple directions and correspondingly research investigations should attempt to mimic these multi-plane movements. An individual is faced with many different situations that they may be required to perform a pulling task. These positions will vary and can significantly affect posture for performing a working task, especially when performed in awkward or difficult working positions.

Haslegrave, Tracy and Corlett (1997) examined force production in awkward positions (notably seated, crouching, standing and reaching overhead) and concluded that working in these awkward positions significantly affected force production. These authors suggest that awkward postures may increase the physiological demands on the system (internal exposure) and thus result in earlier fatigue. They reason that these positions are common and should therefore be examined for successful ergonomic interventions to reduce musculoskeletal injuries.

As indicated, there are a large variety of 'working' postures and each one of these positions has specific characteristics that can significantly change the demands of the task. It is therefore difficult to compare investigations unless there was a common, standardized approach to performing the task. When compared with other characteristics such as handle height, pulling frequency and load, posture is often left out of the standardization process and research participants are left to select their own postures, often leading to confusion and difficulty in comparing research outcomes. In the area of posture, research has focused on a combination of job specific tasks and general positioning while performing a task.

Foot Position

Foot positions often vary and can affect the performance of a pulling task. In a controlled setting it is possible to implement a fixed foot position. Research in this area is lacking but what exists has demonstrated that a fixed foot position does not adversely affect the performance (velocity and kinematics) of a pulling task (MacKinnon, 2002), and more specifically a sub-maximal dynamic pulling task. MacKinnon (2002) investigated the standardization of foot position and the effects on pulling kinematics. With two phases to the experimental design the first phase consisted of collecting the subjects freely chosen foot positions while attempting sub maximal pulls resisted by an iso-inertial load. The second phase consisted of a comparison of the pulling kinematics of a fixed foot position (based on results from the first phase) and a freely chosen foot position. The results of this study concluded that standardization of foot positions during pulling did not significantly affect the pulling kinematics. It was also suggested that for future investigations incorporating a fixed foot position allows for greater control of pulling variables and permits the investigation of body kinematics and kinetics during dynamic pulling activities (MacKinnon, 2002). This work is important as a number of publications (Daams, 1993; Haslegrave, Tracy, & Corlett, 1997) have suggested an adoption of ‘freely-chosen foot postures’ but are open to methodological control criticism. The approach described by MacKinnon (2002) addresses both issues of concern and should be used in future research investigations.

Load

There are many different loads that have been lifted in previous experimental investigations. An underlying similarity between all loads in research investigations is the attempt at simulating a task performed in an industrial or occupational setting. Some of the different attempts at setting an appropriate load have been to simulate the actual load in a task such as mail carts in postal workers, bricklayers, construction workers and airline attendants (Andres & Chaffin, 1991). Researchers have used a fixed load strategy (Hoozemans et al., 1998) and a percentage of absolute body mass (MacKinnon, 2002) as appropriate loads for pulling. When selecting the load it is necessary to consider the goal or outcomes of the research. For example, if the actual task under investigation involves a variable load, or a fixed load, these characteristics should be included in the research design. The load can severely affect the biomechanical performance of the task. Lighter loads are generally performed with single body segments, which are generally small movements that require a limited amount of force production. Larger loads often require full body movements and require a much larger force production to successfully complete the task. A limited amount of research has investigated variable loads and its relationship to biomechanical aspects of pulling. Contrary to what is popularly believed; large loads are not the only dangerous loads a smaller load pulled at a higher frequency can also pose a risk for musculoskeletal injuries.

A large amount of the available research on load investigates actual force production as a dependent variable in the research investigations and do not set it as a control or an independent variable in the research investigation. We believe this is a combination of two common characteristics in pulling research investigations: 1) a common research investigation will ask ‘How does height (or angle, posture, coupling, etc) affect force production?’ and 2) a significant amount of research has been performed with isometric muscular activities. While it is important for standardization and tightly controlled research investigations, we feel it would be more beneficial to attempt functional movements or actual loads in industry.

Pulling Frequency

Pulling frequency is another factor that can affect the biomechanical characteristics of a pulling task. The pulling frequency affects the amount of force that operators are able to output. A higher pulling frequency results in a lower force production, and similarly a low pulling frequency results in higher force production (Ciriello & Snook, 1983). These authors investigated task frequency from once every five (5) seconds to once every eight (8) hours. This difference in force production requirements will affect the muscular recruitment patterns and the body segment/whole body actions that are required to perform the pulling actions.

As with the load lifted, the pulling frequency is often set to simulate a specific task in industry (Hoozemans et al., 1998). As well, often the researchers will not set a specific rate of pulling but rather, they will permit the research participants to self select an appropriate working pace that is based on instructions and estimates of their own working capacity for the specific task.

2.2.3. Biomechanical Future Directions

There exists an overall lack of research investigations into pushing and pulling tasks. The predominant amount of research in this avenue of manual materials handling is on lifting and lowering and not on pushing or pulling tasks. With so few investigations it is difficult to make any conclusions or even comparisons between the research investigations. However, a few early trends seem to be appearing: it seems that the varying postures from investigations may account for the variability that exists in some of the research findings and it has been suggested that posture be controlled for or recorded to maintain consistency. As well, foot positioning control strategies have been successfully implemented and allow for rigorous control of this variable in a laboratory setting. Each of the areas reviewed has specific needs or areas that can be extended through more research.

2.2.4. Summary

In conclusion, this list of pulling characteristics is by no means exhaustive, these variables were selected as areas that are most applicable to a single handed repetitive pulling task as measured in the associated research experiment. The characteristics of the pulling tasks are split into operator-related effects and task-related effects to help distinguish variables and permit a breakdown of the characteristics possibly providing a glimpse into the mechanisms of musculoskeletal injuries. A significant amount of research remains before a causative link between pulling and pushing manual materials handling and musculoskeletal disorders can be determined.

The objective of this study was to measure the changes in trunk kinematic movement strategies and associated EE for three different pulling heights, hip, shoulder and eye. We hypothesize that energy expenditure increases as the level of pulling height increases. As well, trunk kinematics will change from a predominantly twisting motion at the lower pulling heights to more of a forward/backward trunk flexion at the higher pulling heights. These changes in trunk kinematic movement strategies in order to safely perform the pulling task may lead to slight increases in EE.

In order to accomplish this, a randomized repeated measures design was performed with three (3) experimental conditions (hip, shoulder and eye pulling) measuring eight (8) dependent variables (energy expenditure, heart rate, lateral, sagittal and twisting displacements and velocity's).

Chapter 3 – Manuscript

AN INVESTIGATION INTO THE BIOMECHANICAL CHARACTERISTICS AND PHYSIOLOGICAL COST OF THREE STANDARDIZED PULLING TASKS

Grant Handrigan[1]
Geoffrey A Power[1]
Fabien A. Basset[1]
Scott N. MacKinnon[1,2]

[1]School of Human Kinetics and Recreation
Memorial University of Newfoundland
St. John's, NL
Canada A1C 5S7

[2] SafetyNet
INCO Innovation Centre RM 3054
Memorial University of Newfoundland
St. John's, NL
Canada A1C 5S7

✉
Fabien A. Basset
School of Human Kinetics and Recreation
Memorial University,
St. John's, NL
Canada A1C 5S7
Telephone: (709) 737- 6132
E-mail: fbasset@mun.ca

Abstract

Twelve female and seventeen male subjects from a university aged population participated in the study. The subjects were instructed to pull at three heights (hip, shoulder, eye) at a rate of ten pulls per minute, for a period of 10 minutes (one hundred total pulls). The load was fixed at 15% of the subject's absolute body mass. Based on previous research, subjects were instructed to assume a standardized fixed foot position. This was performed in order to control the foot positioning while performing the pulling task. *Statistics:* The data set was verified to satisfy assumptions inherent with a repeated measures analysis of variance (ANOVA). Where main effects existed, a Bonferroni pairwise comparison was performed to determine significance. *Results:* Statistical significance was obtained for energy expenditure ($\dot{E}$), sagittal displacement and twisting velocity. Hip pulling $\dot{E}$ was lower than shoulder pulling $\dot{E}$ (p=.046) and eye pulling $\dot{E}$ (p=.002) by 7% and 11%, respectively. Hip pulling involves less sagittal displacement than shoulder (p=.004) and eye (p=0.001) by 37% and 46%, respectively. Finally, twisting velocity at hip (p=.042) and shoulder (p=.006) pulling were 30% and 36% higher than twisting velocity at eye pulling. *Conclusion:* Physiological data indicate that all three heights of pulling are characterized as 'light' work and an increase in $\dot{E}$ was apparent as the pulling height increased. Trunk kinematics show changes in movement patterns for three standardized pulling tasks. This combined information assists in risk factor identification and the design of appropriate ergonomic interventions.

3.0 Introduction

Manual materials handling (MMH) is a major component of many industrial occupations, and a significant risk factor for musculoskeletal injuries (Pope, 1998). Promoting movement efficiency to reduce overuse is important in manual materials handling. Overuse leads to musculoskeletal injuries in workers; this is both a serious occupational health issue and an increasing economic burden. Occupational ergonomic interventions attempt to reduce the risk of injury and reduce the economic loss. Promoting movement efficiency and low risk activities are an important step in accomplishing this goal; in order to accomplish this, a thorough understanding of the risk factors and proper implementation of appropriate ergonomic design factors is necessary. With an increase in the use of assistive devices to perform MMH, it is also important not to redirect the strain from one body segment to another but to reduce the total strain (Todd, 2005). There is generally a great degree of interaction amongst risk factors in MMH and industrial tasks rarely involve a simple movement. For this reason it is important to approach the task related risk factors in a combinatorial manner, for example, investigating both physiological measurements and trunk kinematics.

A significant amount of industrial tasks involve pulling (Baril-Gingras, 1995), this is particularly true with the increase in use of assistive devices in MMH. In pulling tasks the majority of handle heights range between one meter (from the floor) and shoulder height (Hoozemans et al., 1998). Methods to determine handle heights vary in the research literature, some use a specific height to simulate an industrial task; others use a general approach in examining the effects of different handle heights on pushing and pulling (Chaffin, Andres, & Garg, 1983). Handle heights can affect other task related factors such as the posture, as a result it is necessary to control for these differences and incorporate standardized procedures (MacKinnon, 2002).

It is well known that indirect calorimetry is a reliable and valid method of determining total body energy expenditure ($\dot{E}$). A linear relationship exists between $\dot{E}$ and workload. When performing a variety of tasks, such as three different pulling heights, resultant changes in energy expenditure and trunk kinematics can occur. Quantifying these combined changes can give helpful insights into the multifactorial nature of risk factors for MMH tasks. The aim of this study is to investigate the biomechanical and physiological characteristics of performing a pulling task from three different heights. This combinatorial approach to investigating movement characteristics is a unique and innovative strategy. It is hypothesized that $\dot{E}$ increases as the level of pulling height increases. Furthermore, it is hypothesized that trunk kinematics will change from a predominantly twisting motion at the lower handle heights to more of a forward/backward trunk flexion at the higher handle heights, possibly due to posture changes. These simultaneous changes may be a result of adopted movement strategies to safely perform the pulling tasks.

3.1 Methodology

3.1.1 Subjects

Seventeen (17) male and twelve (12) female subjects voluntarily participated in the study. They are university aged subjects who are inexperienced at performing repetitive pulling and pushing actions. Subject anthropometric characteristics are listed in Table 1. Prior to commencing all subjects were briefed regarding the experimental procedures and then gave their written informed consent in compliance with the Human

Investigations Committee at Memorial University of Newfoundland policy on conducting ethical research. As a screening procedure subjects completed a Physical Activity Readiness Questionnaire (PAR-Q) prior to participating in the study. Subjects were excluded from the study based on the following criteria: left handedness, history of upper limb or back musculoskeletal injuries, and pregnancy.

Insert Table 1 and Figure 1 about here

3.1.2 Experimental Protocol

Subjects underwent three randomized trials at least twenty-four (24) hours apart to allow for sufficient recovery and eliminate any residual fatigue (See Figure 1). Subjects were exposed to three experimental conditions: 1) pulling from hip height 2) pulling from shoulder height and 3) pulling from eye height. The respective anatomical markers are, the anterior superior iliac spine, coracoid process and the sphenoid bone, respectively. The screening session consisted of an information session describing the investigation, obtaining informed consent, collecting anthropometric data (height, weight, age) and performing one of the experimental conditions. The anthropometric data were used to establish the corresponding distances of the fixed foot position, appropriate pulling heights and weight which corresponded to 15% of the subjects absolute body mass (MacKinnon, 2002) (See Figure 2 and Table 1). The fixed foot approach in this study is based on research (MacKinnon, 2002) that sought to determine if a fixed foot position or a freely chosen foot position influenced pulling kinetics and kinematics. It was concluded that a fixed foot position did not significantly differ from a freely chosen foot position. Therefore, the fixed foot position was used throughout all sessions in order to standardize the position of each subject while investigating the kinetic and kinematics of other body segments. All subjects agreed to perform their first experimental condition during their familiarization session. This first session lasted approximately one (1) hour and the remaining sessions lasted approximately one half hour each.

Insert Figure 2 about here

Subjects pulled at a rate of one (1) pull per six (6) seconds (0.16Hz) for ten (10) minutes duration. To ensure consistency of pull frequency, subjects were prompted with a pre-programmed sound, generated by a freely distributed software (Audacity®). The pulling load was determined using a load cell connected in serial with the weight stack and the pulling handle. Statistical comparison revealed no differences between load and the three levels of pulling.

3.1.3 Data Collection

The pulling apparatus is quickly adjustable for pull height and load mass and was modified each session based on individual subject anthropometrics. It consisted of a stack of weight's (4.54kg plates), two (2) pulleys, wire cable and a handle. Force, trunk kinematics and metabolic data were manually synchronized at the start of each session. Each pulling session was videotaped to verify that subjects pulled to a consistent height.

For each pulling segment a visual marker was placed on the pulling apparatus as a cue to what load displacement the subject should obtain.

3.1.4 Kinetics and Kinematics

Pull forces were measured with a strain gauge (HBM® CC100) connected in series to the pulling handle and cable wire (which was run through two pulleys and attached to the load). The pulling force was sampled at 500 Hz using a data acquisition system (IOtech Daqbook/2000®). The strain gauge was calibrated before the experiment by subjecting it to a series of known weights. A three point calibration was used, and from this a regression equation was extracted and used to convert the measured voltages into load forces. A repeated measures analysis of variance on the force data verified that no significant differences existed between the pulling forces for the three pulling heights. Thoracolumbar kinematics were collected using an Acupath Lumbar Motion Monitor (LMM) (NexGen Ergonomics Inc., Pointe Claire, Quebec, Canada). A calibration was performed according to manufacturer specifications prior to each session. The LMM data were collected at 60 Hz and were used to measure thoracolumbar displacements in three three para-anatomical planes (sagittal, mediolateral and transverse). Movements in these three planes will be referred to as frontward / backward flexion, side bending, and twisting, respectively. Due to human error LMM data were available for analysis for only eleven (11) male and eight (8) female of the total twenty-nine (29).

3.1.5 Physiological Measurements

Metabolic data were collected with a portable metabolic system (Sensor Medics® version Vmax ST 1.0) that continuously recorded breath-by-breath samples using a nafion filter tube and a turbine flow meter (opto-electric). Heart rate (HR) values were transmitted via a Polar heart rate monitor (PolarElectro, Kempele, Finland). Prior to testing, gas analyzers and volume were calibrated with medically certified calibration gases (16%O_2 and 3.8% CO_2) and with a 3 litre volume calibration syringe. All gas measurements were standardized with standard temperature pressure and dry (STPD) conditions.

3.1.6 Data Analysis Methods

All kinetic, kinematic and physiological data files were converted and analyzed with MATLAB (MathWorks Inc., Natick, MA). Unprocessed lumbar motion monitor data (displacement and velocity for each motion in lateral, sagittal and twisting directions for each experimental condition) was analyzed at three different time intervals, two (2), five (5) and eight (8) minutes of pulling. For each experimental condition ten of the highest displacements and velocities at each time interval were visually hand marked. This data set was then graphically overlapped with the force data set to confirm pulling was the cause of the motion. Once it was confirmed that pulling was the cause of the motion, mean and standard deviations were calculated for these 10 data points for each of the three time intervals.

Physiological Measurements

Pre- and post-pulling metabolic data were truncated and only the ten (10) minute pulling segment was integrated and allometrically scaled to find total energy expenditure for a ten (10) minute pulling session. Oxygen consumption values were then converted and expressed as $\dot{E}$ (kJ) (Ferrannini, 1988). Heart rate was sampled at one (1) Hz and mean ± SD were calculated for each test. It is noteworthy to mention that $\dot{E}$ data were not segmented as the kinematics data because of a clear ten (10) minute metabolic steady state, that is, participants reached a level of energy cost and continued at this steady rate until the task was completed.

3.1.7 Statistical analysis

All data are presented as mean and standard deviation unless otherwise specified. The dependent variables are $\dot{E}$ and trunk kinematics. The independent factor is the three heights of pulling. First, a one-way analysis of variance with repeated measures on the factor height (hip, shoulder and eye) was performed on metabolic data. Second, a three-way analysis of variance (2 sex x 3 heights x 3 times) was performed on kinematics. Prior to running ANOVA data sets were verified for normality (Wilk-Shapiro, Lilliefors test, and Kolmogorov-Smirnov test). As well, the assumption of sphercity was also tested and in the event that the data did not meet the criteria, adjusted epsilon (ε) values (Greenhouse-Geisser) were used. When statistical significance was reached (alpha level of $p \leq 0.05$), Bonferroni adjusted pairwise comparisons were considered to identify where significant mean differences occurred. The Statistical Package for Social Sciences SPSS (version 14) was used for all statistical analyses (SPSS INC., Chicago, USA).

3.2 Results

Results are reported as physiological measurements and kinematics parameters. Physiological data ($\dot{E}$ and heart rate) were analyzed by separating hip, shoulder and eye. The trunk displacements (degrees) and velocities (degrees•sec^{-1}) are reported for frontward / backward flexion, side bending, and twisting. They were also separated into three one (1) minute windows for a time effect analysis. Finally, they were further separated by pulling height.

3.2.1 Physiological Measurements

The first statistical analysis that was performed indicates no significant difference between sexes for the physiological measurements. Based on this finding, subsequent analyses considered pooled data. Mean ± SD values for $\dot{E}$ (kJ) and heart rate (bpm) are presented in table 3 There was a main-significant effect of height on $\dot{E}$ (p=.001). Pairwise comparisons revealed that hip pulling $\dot{E}$ was lower than shoulder $\dot{E}$ (p=.046) and eye $\dot{E}$ (p=.002) by 7% and 11%, respectively. As the height of pulling increased (hip to shoulder to eye) the $\dot{E}$ increased

Along with the above results there was a main significant effect of height on heart rate (p=.001). Pairwise comparisons further showed heart rate for hip pulling was 9% lower than eye pulling (p=.001).

Insert Table 2 about here

3.2.2 Kinematics Measurements

No significant differences for pulling heights on side bending displacements were found. However, there was a main significant time effect (p=.015) on side bending velocities. Further *post hoc* analysis showed that the velocity is 15% lower for the two (2) minute time segment than for the eight (8) minute segment (p=.025). Despite this significant outcome, the one (1) degree difference between two (2) and eight (8) minute segments is believed to be clinically irrelevant and beyond measurement accuracy of the device for side bending displacements and velocities (LMM error measurement of 1.71 °; see Marras et al., 1992).

There was a main significant effect of height on frontward / backward flexion displacements (p=0.001); *Post hoc* analysis showed hip pulling involved less movement than shoulder (p=.004) and eye (p=0.001) by 37% and 46%, respectively. There was also a main significant time effect on the same dependant variable (p=0.009). Pairwise comparisons showed that the two (2) minute time segment has a 19% lower displacement than the eight (8) minute time segment (p=0.035). Concurrently, there was a main significant effect of height on frontward / backward flexion velocities (p=.001). Pairwise comparisons revealed that hip pulling velocity is lower than shoulder (p=.003) and eye pulling (p=.005) by 44% and 48%, respectively.

There was no significant effect of height on twisting displacements but the *p*-values for hip to eye (p= 0.07) and shoulder to eye (0.062) were close to significance and are supported by the velocity outcome, which showed a main significant height effect (p=.002) on twisting velocities. *Post hoc* analysis further showed that hip (p=.042) and shoulder (p=.006) pulling were 30% and 36% higher than the twisting velocity at eye pulling. The statistical analysis further revealed a significant interaction between time and sex for pulling heights on twisting displacements. *Post hoc* revealed, the significant differences were between sexes for time two (2) only (p=0.003). This result has to be taken with caution because through scrutinizing the data, mean displacements in all conditions for females are higher compared to males (Females: Hip Time 2,5,8 minute segment= 19.35±4.5, 16.9±6.2, 20.3±9,2, Shoulder Time 2,5,8 minute segment= 23.8±13.8, 20±9.6, 21.2±7.3 and Eye Time 2,5,8 minute segment=16.1±11.2, 16±8.6, 16.7±11.4; Males: Hip Time 2, 5, 8 minute segment= 11.2±6.9, 14.8±7, 15.9±9; Shoulder Time 2, 5, 8 minute segment= 10.3±5.8, 12.1±7.8, 12.4±7.4; and Eye Time 2, 5, 8 minute segment= 7.7±3.8, 9.9±5.5, 10.5±7). These may result from the high variability between- and within-subjects in all conditions for this dependent variable.

3.3 Discussion

The aim of this study was to investigate the effects of pulling height on $\dot{E}$ and trunk kinematics. Physiological outcomes were an increase in $\dot{E}$ and HR as the pulling height increased; and accommodations were made in trunk kinematics for each pulling height. Through an integrative approach, combining physiological and biomechanical data provides additional information that will assist in the investigation of risk factors for manual materials handling and identifying appropriate ergonomic design interventions.

Foot positions often vary and can affect posture while performing a pulling task and can lead to different biomechanical task performance features. To minimize this effect, the present protocol included a standardized foot position that was shown to not significantly affect the pulling kinetics and kinematics. It was suggested that for future investigations incorporating a fixed foot position allows for greater control of pulling variables and permits the investigation of body kinematics and kinetics during dynamic pulling activities (MacKinnon, 2002).

The main physiological results of the study demonstrate that $\dot{E}$ for shoulder and eye pulling was higher than hip pulling. The task was designed to simulate ten (10) minutes of pulling for a typical eight (8) hour workday. However, if we extrapolate from the ten (10) minute sample to a full workday, assuming three (3) of the eight (8) hours are spent performing the pulling task, we have a better understanding of the actual physiological strain. Simulating the three (3) hour work session leads to these approximate $\dot{E}$ (kJ): 2214±658, 2365±694 and 2496±694 for hip, shoulder and eye, respectively. These calculations were computed from the caloric equivalents equations (Ferrannini, 1988) and converted into kilojoules. These energy expenditures are statistically significant (data not shown) and are classified as 'light' work that is suitable to perform over an eight hour workday (Astrand, 1986). This assertion that the tasks were light work is confirmed by the slight significant increase in heart rate as the height of pulling increased (105±3, 110±3, 115±4 for hip, shoulder, and eye, respectively). Although heart rate showed a similar linear increase, as did $\dot{E}$, statistical outcomes do not exactly mirror each other (heart rate statistical significance was only reached between hip and eye pulling). Although a number of studies have shown that heart rate and oxygen uptake are strongly correlated with the workload during aerobic exercise (Basset & Boulay, 2000), the current observation leads to question the validity of using only heart rate as a measure of $\dot{E}$ for light work tasks.

Finally, sex differences exist when examining working capabilities. These differences are often interpreted as basic physical and anthropometrical differences between sexes, including differences in strength and aerobic capacity (Charkoudian &

Joyner, 2004). In this study no sex difference was found perhaps due to the light work requirements of the task and the use of a similar relative pulling load.

In the present experiment, the frontward / backward flexion displacements and velocities indicate that for hip pulling, there was less displacement and a comparably lower velocity for shoulder and eye pulling height. Inversely, twisting displacements and velocities were lower at shoulder and eye pulling height compared to hip pulling height. Recall that only twisting velocities were significantly different. These results confirmed previous research that highlighted handle height affects movement pattern (Ayoub & MacDaniel, 1974). It further supports other experimental outcomes that movements often encompass multiple directions (Resnick & Chaffin, 1995). At shoulder and eye pulling heights, the shoulder is not in an optimized position to perform the task (Kee & Karwowski, 2001). The shoulder joint is abducted at least 90°, this moves the center of gravity away from the body core resulting in a position which requires a moment of force in the sagittal plane to stabilize the arm. Therefore, to compensate for these additional demands trunk movements are necessary, which may increase the overall physiological stress as reflected by increases in VO_2 and HR. For hip pulling height, the shoulder is in a neutral position minimizing the moment of the force of gravity on the arm and reducing the energy requirements for maintaining the position.

Statistical outcomes revealed a significant time effect for sagittal displacement (forward/backward displacement) for all three pulling heights. This indicates the trunk kinematics changed throughout the course of the ten (10) minute pulling session. The pulling task was designed to simulate low intensity, long duration work (approximately eight hour workdays). It is interesting to note that over such a short time period, a change in movement patterns (from a predominantly twisting pattern at lower heights to a predominantly frontward/backward flexion at higher pulling heights) at the thoracolumbar segment was observed. This might be a result of fatigue from performing the pulling tasks. One other possible explanation is that this could be a task learning effect leading to the greatest movement efficiency. It is possible that throughout the eye pulling height trial as the participants experienced an uncomfortable arm position it led to movement adjustments that may limit fatigue or risk of injury.

Although the tasks in the current experiment are classified as light work, the metabolic device was sensitive enough to capture the total body $\dot{E}$ differences between pulling heights. The novelty of this experimental design comes from the theoretical integration of biomechanical and physiological parameters to study the acute responses in manual materials handling. This study brings new information regarding the relationship between $\dot{E}$ and movement patterns. In fact, the data showed that accommodations in movement patterns were accompanied by metabolic rate adjustments between different pulling heights. Regardless of the different movement patterns between pulling heights the metabolic data suggest hip pulling height is less demanding and, potentially less fatiguing than shoulder and eye pulling heights.

Marras et al. (1995) investigated biomechanical risk factors for occupationally related low back disorders (LBD). They proposed the use of the LMM and documented the use in a variety of industrial job investigations. From this data they developed a combined model that included five (5) risk factors for LBD: load weight, lift rate, maximum sagittal angle, lateral velocity and twisting velocity; and a classification system for quantifiable comparisons and ratings of trunk kinematics into low, medium and high risk for LBD. When our pulling trunk kinematics are compared with his model we obtain the following: sagittal velocity at shoulder and eye pulling heights are rated 'medium' and 'high ' risk, respectively, and for twisting velocities all pulling heights are rated 'high risk'. Low risk classifications are obtained for all of the remaining movements. This classification for the trunk kinematics indicates that the movements in our study may be precursors to LBD in inexperienced individuals.

3.4 Conclusion

In summary, differences in energy expenditure and trunk kinematics for three different standardized pulling tasks are presented. From a physiological standpoint, these pulling tasks were characterized as light work that is suitable for a typical workday, and from a biomechanical perspective several of the trunk kinematics for the three pulling heights were rated medium or high risk for developing LBD. This information provides insight into the need for holistic approaches to assess MMH in future research investigations and their sometimes conflicting nature. Therefore, when designing ergonomic interventions we recommend to use a comprehensive approach to resolving design issues.

3.5 Future Directions and Limitations

To determine if pulling experience changes these outcomes, future investigations into movement efficiency may use individuals that have pulling experience as this might highlight different trunk kinematics for the three pulling tasks. It would also be interesting to see if by restricting and controlling the trunk movements would energy expenditure increase to an even greater extent than when the trunk is free to move and adopt different trunk kinematics. A limitation in our study was only including one pulling task at three heights to analyze trunk kinematics and energy expenditure differences. A larger variety of tasks and heights would provide more insights into the risks of performing manual materials handling.

3.6 References

Astrand, P-O., and Rodahl, K. (1986). *Textbook of Work Physiology.* New York: McGraw-Hill Press.

Ayoub, M. M., McDaniel, J.W. (1974). Effects of operator stance on pushing and pulling tasks. *American Institute of Industrial Engineering Transactions, 6*, 185-195.

Baril-Gingras, G. a. L., M.,. (1995). The handling of objects other than boxes: univariate analysis of handling techniques in a large transport company. *Ergonomics, 38*, 905-925.

Basset, F. A., & Boulay, M. R. (2000). Specificity of treadmill and cycle ergometer tests in triathletes, runners and cyclists. *Eur J Appl Physiol, 81*(3), 214-221.

Boocock, M. G., Haslam, R. A., Lemon, P., & Thorpe, S. (2006). Initial force and postural adaptations when pushing and pulling on floor surfaces with good and reduced resistance to slipping. *Ergonomics, 49*(9), 801-821.

Charkoudian, N., & Joyner, M. J. (2004). Physiologic considerations for exercise performance in women. *Clin Chest Med, 25*(2), 247-255.

Ciriello, V. M., & Snook, S. H. (1983). A study of size, distance, height, and frequency effects on manual handling tasks. *Hum Factors, 25*(5), 473-483.

de Looze, M. P., Urlings, I. J., Vink, P., van Rhijn, J. W., Miedema, M. C., Bronkhorst, R. E., et al. (2001). Towards successful physical stress reducing products: an evaluation of seven cases. *Appl Ergon, 32*(5), 525-534.

Dempsey, P. G. (1998). A critical review of biomechanical, epidemiological, physiological and psychophysical criteria for designing manual materials handling tasks. *Ergonomics, 41*(1), 73-88.

Ferrannini, E. (1988). The theoretical bases of indirect calorimetry: a review. *Metabolism, 37*(3), 287-301.

Ferrari, M., Mottola, L., & Quaresima, V. (2004). Principles, techniques, and limitations of near infrared spectroscopy. *Can J Appl Physiol, 29*(4), 463-487.

Frymoyer, J. W., Pope, M. H., Costanza, M. C., Rosen, J. C., Goggin, J. E., & Wilder, D. G. (1980). Epidemiologic studies of low-back pain. *Spine, 5*(5), 419-423.

Garg, A., & Beller, D. (1990). One-Handed Dynamic Pulling Strength with Special Reference to Speed, Handle Height and Angles of Pulling. *International Journal of Industrial Ergonomics, 6*, 231-240.

Gill, K. P., & Callaghan, M. J. (1996). Intratester and intertester reproducibility of the lumbar motion monitor as a measure of range, velocity and acceleration of the thoracolumbar spine. *Clin Biomech (Bristol, Avon), 11*(7), 418-421.

Hignett, S., Wilson, J. R., & Morris, W. (2005). Finding ergonomic solutions--participatory approaches. *Occup Med (Lond), 55*(3), 200-207.

Hoozemans, M. J., van der Beek, A. J., Frings-Dresen, M. H., van der Woude, L. H., & van Dijk, F. J. (2002). Pushing and pulling in association with low back and shoulder complaints. *Occup Environ Med, 59*(10), 696-702.

Hoozemans, M. J., van der Beek, A. J., Frings-Dresen, M. H., van Dijk, F. J., & van der Woude, L. H. (1998). Pushing and pulling in relation to musculoskeletal disorders: a review of risk factors. *Ergonomics, 41*(6), 757-781.

Kee, D., & Karwowski, W. (2001). LUBA: an assessment technique for postural loading on the upper body based on joint motion discomfort and maximum holding time. *Applied Ergonomics, 32*(4), 357-366.

Kelsey, J. L., Golden, A. L., & Mundt, D. J. (1990). Low back pain/prolapsed lumbar intervertebral disc. *Rheum Dis Clin North Am, 16*(3), 699-716.

Kingma, I., Bosch, T., Bruins, L., & van Dieen, J. H. (2004). Foot positioning instruction, initial vertical load position and lifting technique: effects on low back loading. *Ergonomics, 47*(13), 1365-1385.

Koningsveld, E. A., & van der Molen, H. F. (1997). History and future of ergonomics in building and construction. *Ergonomics, 40*(10), 1025-1034.

MacKinnon, S. N. (2002). Effects of standardized foot positions during the execution of a submaximal pulling task. *Ergonomics, 45*(4), 253-266.

Marras, W. S., Fathallah, F.A., Miller, R.J., Davis, S.W., Mirka,G.A., . (1992). Accuracy of a three-dimensional lumbar motion monitor for recording dynamic trunk motion characteristics. *International Journal of Industrial Ergonomics, 9*, 75-87.

Marras, W. S., Parnianpour, M., Ferguson, S. A., Kim, J. Y., Crowell, R. R., Bose, S., et al. (1995). The classification of anatomic- and symptom-based low back disorders using motion measure models. *Spine, 20*(23), 2531-2546.

Neary, J. P., & Bhambhani, Y. N. (2004). Near infrared spectroscopy: from the "black box to the ice arena". Symposium introduction. *Can J Appl Physiol, 29*(4), 461-462.

Pope, M. H. (1998). Does manuel materials handling cause low-back pain? *International Journal of Industrial Ergonomics, 22*, 489-492.

Resnick, M. L., & Chaffin, D. B. (1995). An ergonomic evaluation of handle height and load in maximal and submaximal cart pushing. *Appl Ergon, 26*(3), 173-178.

Snook, S. H. (1978). The design of manual handling tasks. *Ergonomics, 21*(12), 963-985.

Snook, S. H., Campanelli, R. A., & Hart, J. W. (1978). A study of three preventive approaches to low back injury. *J Occup Med, 20*(7), 478-481.

Todd, A., I. (2005). Current Trends in Research Focused on Pushing and Pulling. *Ergonomics South Africa, 2*, 42-53.

Figure Captions

Figure 1 – Experimental timeline for the data collection process. Three sessions in total, where the first session comprised of informed consent, anthropometric data and the first randomized experimental condition. The remaining two sessions comprised of randomized experimental conditions two and three.

Figure 2 – A) Front view of equipment placement and experimental setup on subject. The subject is equipped with a portable metabolic cart that is affixed to a pc, has the pulling handle (with load cell connected in serial) in hand and at hip height, and is in a standardized foot position. B) Subjects standardized foot positions as described in Mackinnon (1998). Each subject's anthropometric data was collected to determine their standardized foot position in order to control for posture and other body segments.

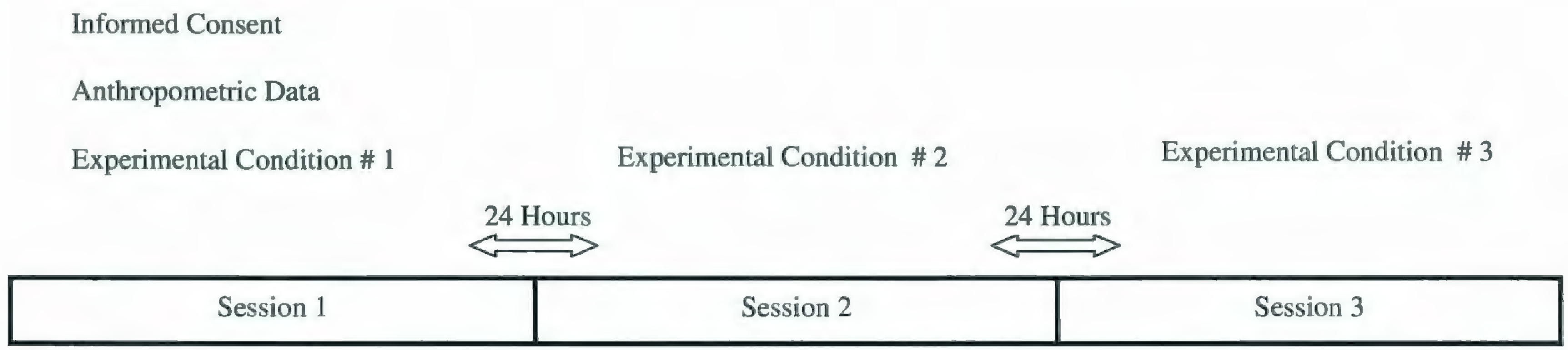

Figure 1 - Experimental Timeline

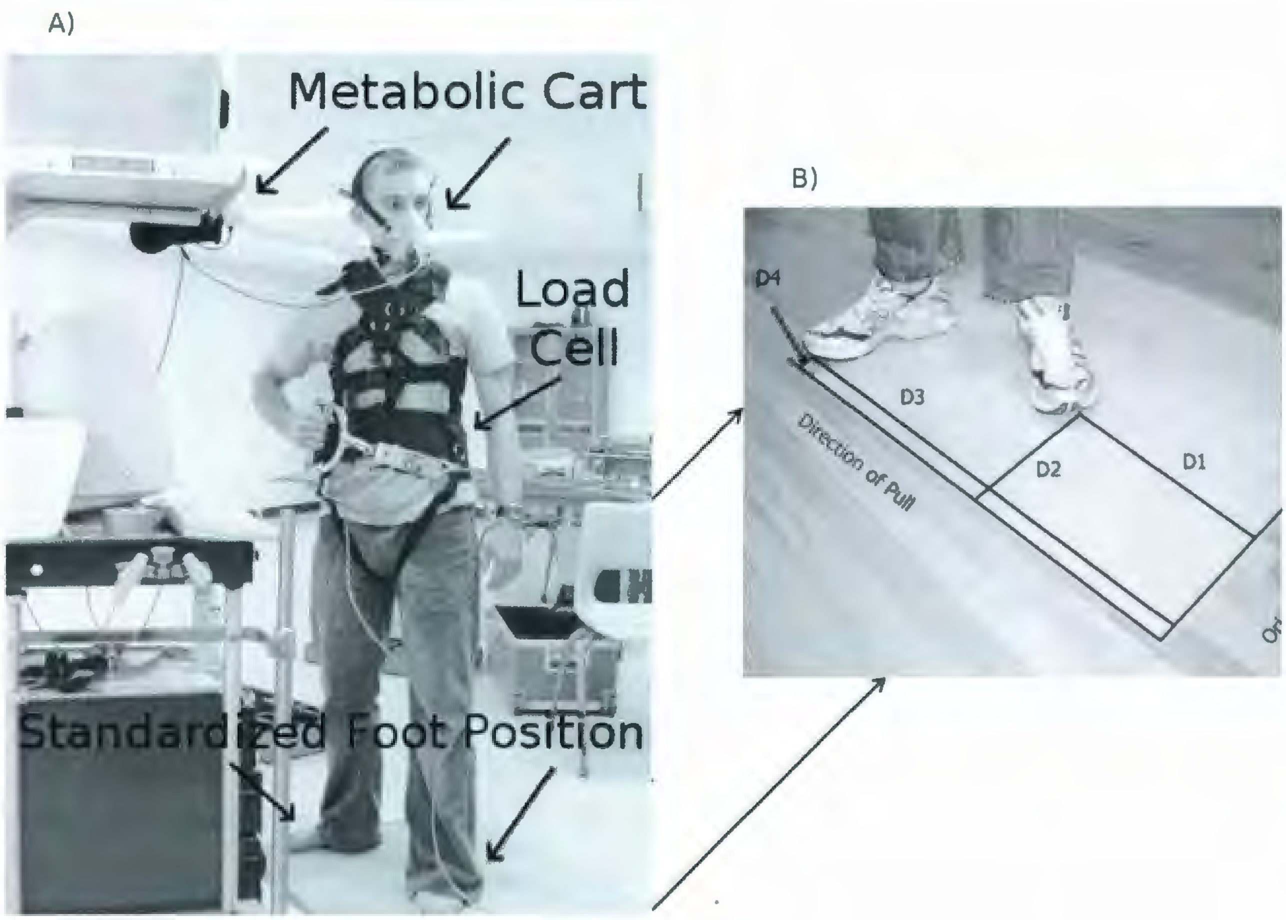

Figure 2 - Experimental Setup and Standardized Foot Position

Table 1 – Subject Characteristics

	Male	Female
Age (years)	23 ± 2.5	23 ± 2
Height (cm)	177 ± 9.0	169 ± 4
Body Mass (kg)	78 ± 18	63 ± 7
D1 (cm)	33.7 ± 1.8	32.2 ± 0.9
D2 (cm)	15.3 ± 0.8	14.6 ± 0.4
D3 (cm)	82.9 ± 4.3	79.2 ± 2.2
D4 (cm)	0.7 ± 0.1	0.69 ± 0.02
Load (kg)	15.5 ± 3.6	12.6 ± 1.5

mean ± sd

Table 2 - Trunk Kinematics

		Side Bending			Front Backward Bending			Twisting		
		Time 2	Time 5	Time 8	Time 2	Time 5	Time 8	Time 2	Time 5	Time 8
Displacement (degrees)	Hip	**6.44±3.13**	**6.52±4.6**	**6.46±3.5**	**4.72±2.3**	**5.73±3.7**	**5.86±3.4**	**14.6±7.1**	**15.69±6.6**	**17.8±9.1**
		(4.93, 7.95)	(4.30, 8.74)	(4.78, 8.15)	(3.61, 5.83)	(3.95, 7.51)	(4.20, 7.53)	(11.19, 18.1)	(12.51, 18.9)	(13.4, 22.2)
	Shoulder	**6.83±2.6**	**6.98±2.5**	**6.55±3.0**	**7.85±3.8**	**9.15±4.3**	**9.31±3.31**	**15.94±11.8**	**15.41±9.2**	**16.13±8.4**
		(5.59, 8.08)	(5.78, 8.17)	(5.10, 7.99)	(6.03, 9.66)	(7.08, 11.21)	(7.71, 10.9)	(10.25, 21.64)	(10.96, 19.86)	(12.08, 20.17)
	Eye	**6.72±4.0**	**8.00±4.6**	**8.04±3.6**	**8.82±3.9**	**9.94±5.8**	**11.43±5**	**11.2±9.3**	**12.47±7.4**	**13.1±9.3**
		(4.81, 8.63)	(5.79, 10.2)	(6.33, 9.75)	(6.94, 10.69)	(7.14, 12.74)	(9.04, 13.83)	(5.75, 15.66)	(8.9, 16.04)	(8.6, 17.61)
Velocity (degrees • sec^{-1})	Hip	**6.18±3.1**	**6.43±3.4**	**7.10±3.3**	**7.36±3.9**	**8.32±3.9**	**8.25±4.1**	**14.92±9.5**	**18.08±12**	**17.22±10.5**
		(4.67, 7.68)	(4.79, 8.07)	(5.50, 8.68)	(5.46, 9.26)	(6.43, 10.21)	(6.25, 10.24)	(10.36, 19.48)	(12.31, 23.84)	(12.16, 22.29)
	Shoulder	**5.63±1.8**	**6.34±2.5**	**6.67±2.4**	**11.4±5**	**11.92±5.3**	**12.9±6.6**	**16.7±11.8**	**16.13±11.3**	**18.37±12.5**
		(4.78, 6.49)	(5.13, 7.56)	(5.51, 7.82)	(8.97, 13.83)	(9.36, 14.47)	(9.73, 16.06)	(11.07, 22.39)	(10.66, 21.6)	(12.35, 24.4)
	Eye	**5.85±2.7**	**6.08±2.8**	**6.9±4.4**	**13.45±8.71**	**15.62±10.2**	**15.28±10.9**	**13.14±8.9**	**10.80±8.2**	**14.06±13.6**
		(4.57, 7.13)	(4.73, 7.44)	(4.79, 9.01)	(9.25, 17.65)	(10.7, 20.54)	(10, 20.55)	(8.85, 17.43)	(6.84, 14.75)	(7.48, 20.63)

mean ± sd
(C.I. at 95%)

Table 3 - Energy Expenditure

Pulling Height	Energy Expenditure (kJ)	Heart Rate (bpm)
Hip	123±37	105±16
Shoulder	131±39*	109±19
Eye	139±42*	115±20*

mean ± sd
* stastically different than hip

Chapter 4 – Further Explanations on Experimental Investigation

4.1 Response to the Research Hypothesis

A research hypothesis was energy expenditure will increase as the level of pulling height increases. As well, trunk kinematics will change from a predominantly twisting motion at the lower handle heights to more of a forward/backward trunk flexion at the higher handle heights. Our results support the increases in energy expenditure with increases in the level of pulling. As the height of pulling increased from hip to shoulder to eye the energy expenditure went up accordingly. The overall increase in energy expenditure was statistically significant, and all of the pulling heights were within a physiological load categorization of 'light work'. Trunk kinematics behaved exactly as hypothesized, as the level of pulling increased the movement strategies of the trunk adjusted from a predominantly twisting (at hip) action to a backward/forward (at eye) action. These changes were statistically significant and according to one low back disorder model (Marras et al., 1995), biologically significant as a predictor of injury in inexperienced individuals.

4.2 Limitations

Many task related factors exist as a risk factor for predicting musculoskeletal injuries. This prospective study aimed to investigate energy expenditure and trunk kinematics for three standardized pulling tasks. Many MMH risk factors are related and often interact with each other to increase the risk of injury. As a limitation of this study, we only investigated one specific task from three different heights; to improve on this we could investigate multiple different pulling and pushing tasks to understand the energy expenditure and trunk kinematic changes for multiple tasks, As well, this study is not meant to directly predict musculoskeletal injuries, but rather should be viewed as additional information that can be used in the search for risk factors and appropriate ergonomic design interventions.

4.2.1 Subjects

Subjects for this investigation were a sample comprised mainly of University aged individuals with limited or no experience working in industrial occupations, and no history of operating pulling or assistive devices. This is a limitation in measuring the physiological load of the pulling task and thus in assessing the LBD risk, as experienced individuals might have movement efficiency or economy not seen with inexperienced individuals.

4.2.2 Measurement

Equipment and investigator measurement errors exist in all research investigations. Possible sources of error in this investigation are lumbar motion monitor, portable metabolic system, and the calibrations for each measurement device. Investigators adhered strictly to the calibration guidelines for both equipment and attempted to limit the amount of error introduced by the measurement equipment.

4.2.3 Experimental Design

As with any study conducted in a laboratory setting it is difficult to replicate industrial conditions. There are limitations inherent with this design, such as the brief instructions to perform the task (Kingma, Bosch, Bruins, & van Dieen, 2004), and that the pulling frequency and load (% of absolute body mass) were fixed for all subjects. This was an attempt to simulate a repetitive, submaximal pulling task in an occupational setting, as this protocol was the only protocol investigated, only tasks specific to this protocol should use our results and suggestions as a model.

The original goal was to select a task (height, load, frequency) that would be appropriate to simulate the requirements of an eight-hour working day. Ciriello and Snook (1978) selected a 40 minute period as the appropriate amount of time to accurately estimate worker capabilities for an eight-hour workday. Based on this criterion, the workload was collected over a considerably shorter time period and as a result is probably better suited to simulate the performance of intermittent pulling activity of a ten minute duration.

4.3 Concluding Remarks

In conclusion, this is a prospective study that measured the energy expenditure and trunk kinematics of three separate heights of pulling- hip, shoulder and eye level. The initial goal of providing additional information to the growing body of information on risk factor analysis and the prediction of musculoskeletal injuries in inexperienced workers was achieved.

4.4 References

Andres, R. O., & Chaffin, D. B. (1991). Validation of a biodynamic model of pushing and pulling. *J Biomech, 24*(11), 1033-1045.

Ayoub, M. M., McDaniel, J.W. (1974). Effects of operator stance on pushing and pulling tasks. *Am Ins Ind Eng Trans, 6*, 185-195.

Baril-Gingras, G. a. L., M.,. (1995). The handling of objects other than boxes: univariate analysis of handling techniques in a large transport company. *Ergonomics, 38*, 905-925.

Brooks, G. A., Fahey, T. D., Baldwin, K. M., (Ed.). (2004). *Exercise physiology: human bioenergetics and its applications* (4th ed.): McGraw Hill Higher Education.

Boocock, M. G., Haslam, R. A., Lemon, P., & Thorpe, S. (2006). Initial force and postural adaptations when pushing and pulling on floor surfaces with good and reduced resistance to slipping. *Ergonomics, 49*(9), 801-821.

Chaffin, D. B. (1987). Manual materials handling and the biomechanical basis for prevention of low-back pain in industry--an overview. *Am Ind Hyg Assoc J, 48*(12), 989-996.

Chaffin, D. B. (2005). Primary prevention of low back pain through the application of biomechanics in manual materials handling tasks. *G Ital Med Lav Ergon, 27*(1), 40-50.

Chaffin, D. B., Andres, R. O., & Garg, A. (1983). Volitional postures during maximal push/pull exertions in the sagittal plane. *Hum Factors, 25*(5), 541-550.

Chaffin, D. B., Nussbaum, M.A. (1999). Effects of Pacing When Using Material Handling Manipulators. *Hum Factors, 41*(2), 214-225.

Charkoudian, N., & Joyner, M. J. (2004). Physiologic considerations for exercise performance in women. *Clin Chest Med, 25*(2), 247-255.

Cheng, T. S., & Lee, T. H. (2004). Human pulling strengths in different conditions of exertion. *Percept Mot Skills, 98*(2), 542-550.

Ciriello, V. M., & Snook, S. H. (1983). A study of size, distance, height, and frequency effects on manual handling tasks. *Hum Factors, 25*(5), 473-483.

Ciriello, V. M., Snook, S. H., & Hughes, G. J. (1993). Further studies of psychophysically determined maximum acceptable weights and forces. *Hum Factors, 35*(1), 175-186.

Cust, G., Pearson, J. C., & Mair, A. (1972). The prevalence of low back pain in nurses. *Int Nurs Rev, 19*(2), 169-179.

Damlund, M., Goth, S., Hasle, P., & Munk, K. (1982). Low-back pain and early retirement among Danish semiskilled construction workers. *Scand J Work Environ Health, 8 Suppl 1*, 100-104.

Datta, S. R., Chatterjee, B. B., & Roy, B. N. (1978). The energy cost of rickshaw pulling. *Ergonomics, 21*(11), 879-886.

Datta, S. R., Chatterjee, B. B., & Roy, B. N. (1983). The energy cost of pulling handcarts ('thela'). *Ergonomics, 26*(5), 461-464.

David, G. C. (2005). Ergonomic methods for assessing exposure to risk factors for work-related musculoskeletal disorders. *Occup Med (Lond), 55*(3), 190-199.

de Looze, M. P., Urlings, I. J., Vink, P., van Rhijn, J. W., Miedema, M. C., Bronkhorst, R. E., et al. (2001). Towards successful physical stress reducing products: an evaluation of seven cases. *Appl Ergon, 32*(5), 525-534.

Dempsey, P. G. (1998). A critical review of biomechanical, epidemiological, physiological and psychophysical criteria for designing manual materials handling tasks. *Ergonomics, 41*(1), 73-88.

Dempsey, P. G. (2003). A survey of lifting and lowering tasks. *International Journal of INdustrial Ergonomics, 31*(1), 11-16.

Ferrannini, E. (1988). The theoretical bases of indirect calorimetry: a review. *Metabolism, 37*(3), 287-301.

Ferrari, M., Mottola, L., & Quaresima, V. (2004). Principles, techniques, and limitations of near infrared spectroscopy. *Can J Appl Physiol, 29*(4), 463-487.

Frymoyer, J. W., Pope, M. H., Costanza, M. C., Rosen, J. C., Goggin, J. E., & Wilder, D. G. (1980). Epidemiologic studies of low-back pain. *Spine, 5*(5), 419-423.

Garg, A., & Beller, D. (1990). One-Handed Dynamic Pulling Strength with Special Reference to Speed, Handle Height and Angles of Pulling. *Intl J Ind Ergon, 6*, 231-240.

Gill, K. P., & Callaghan, M. J. (1996). Intratester and intertester reproducibility of the lumbar motion monitor as a measure of range, velocity and acceleration of the thoracolumbar spine. *Clin Biomech (Bristol, Avon), 11*(7), 418-421.

Grieve, D. W. (1983). Slipping due to manual exertion. *Ergonomics, 26*(1), 61-72.

Gronqvist, R., Abeysekera, J., Gard, G., Hsiang, S. M., Leamon, T. B., Newman, D. J., et al. (2001). Human-centred approaches in slipperiness measurement. *Ergonomics, 44*(13), 1167-1199.

Hignett, S., Wilson, J. R., & Morris, W. (2005). Finding ergonomic solutions--participatory approaches. *Occup Med (Lond), 55*(3), 200-207.

Hoozemans, M. J., van der Beek, A. J., Frings-Dresen, M. H., van der Woude, L. H., & van Dijk, F. J. (2002). Pushing and pulling in association with low back and shoulder complaints. *Occup Environ Med, 59*(10), 696-702.

Hoozemans, M. J., van der Beek, A. J., Frings-Dresen, M. H., van Dijk, F. J., & van der Woude, L. H. (1998). Pushing and pulling in relation to musculoskeletal disorders: a review of risk factors. *Ergonomics, 41*(6), 757-781.

Kelsey, J. L., Golden, A. L., & Mundt, D. J. (1990). Low back pain/prolapsed lumbar intervertebral disc. *Rheum Dis Clin North Am, 16*(3), 699-716.

Kingma, I., Bosch, T., Bruins, L., & van Dieen, J. H. (2004). Foot positioning instruction, initial vertical load position and lifting technique: effects on low back loading. *Ergonomics, 47*(13), 1365-1385.

Koningsveld, E. A., & van der Molen, H. F. (1997). History and future of ergonomics in building and construction. *Ergonomics, 40*(10), 1025-1034.

Kumar, S. (2001). Theories of musculoskeletal injury causation. *Ergonomics, 44*(1), 17-47.

Kumar, S., Narayan, Y., & Bacchus, C. (1995). Symmetric and asymmetric two-handed pull-push strength of young adults. *Hum Factors, 37*(4), 854-865.

Lee, K. S., Chaffin, D. B., Herrin, G. D., & Waikar, A. M. (1991). Effect of handle height on lower-back loading in cart pushing and pulling. *Appl Ergon, 22*(2), 117-123.

Li, G., & Buckle, P. (1999). Current techniques for assessing physical exposure to work-related musculoskeletal risks, with emphasis on posture-based methods. *Ergonomics, 42*(5), 674-695.

Li, K. W., Yu, R. F., & Han, X. L. (2007). Physiological and psychophysical responses in handling maximum acceptable weights under different footwear-floor friction conditions. *Appl Ergon, 38*(3), 259-265.

Lloyd, M. H., Gauld, S., & Soutar, C. A. (1986). Epidemiologic study of back pain in miners and office workers. *Spine, 11*(2), 136-140.

MacKinnon, S. N. (2002). Effects of standardized foot positions during the execution of a submaximal pulling task. *Ergonomics, 45*(4), 253-266.

Marras, W. S. (2000). Occupational low back disorder causation and control. *Ergonomics, 43*(7), 880-902.

Marras, W. S., Fathallah, F.A., Miller, R.J., Davis, S.W., Mirka,G.A., . (1992). Accuracy of a three-dimensional lumbar motion monitor for recording dynamic trunk motion characteristics. *International Journal of Industrial Ergonomics, 9*, 75-87.

Marras, W. S., Parakkat, J., Chany, A. M., Yang, G., Burr, D., & Lavender, S. A. (2006). Spine loading as a function of lift frequency, exposure duration, and work experience. *Clin Biomech (Bristol, Avon), 21*(4), 345-352.

Marras, W. S., Parnianpour, M., Ferguson, S. A., Kim, J. Y., Crowell, R. R., Bose, S., et al. (1995). The classification of anatomic- and symptom-based low back disorders using motion measure models. *Spine, 20*(23), 2531-2546.

Martin, B. J., and Chaffin, D.B. (1972). Biomechanical Computerized Simulation of Human Strength in Sagittal Plane Activities. *AIIE Transactions, 4*(1).

Miller, A. E., MacDougall, J. D., Tarnopolsky, M. A., & Sale, D. G. (1993). Gender differences in strength and muscle fiber characteristics. *Eur J Appl Physiol Occup Physiol, 66*(3), 254-262.

Mital, A., Nicholson, A.S., Ayoub, M.M. (1993). *A guide to manual materials handling*. London: Taylor & Francis.

Neary, J. P., & Bhambhani, Y. N. (2004). Near infrared spectroscopy: from the "black box to the ice arena". Symposium introduction. *Can J Appl Physiol, 29*(4), 461-462.

Resnick, M. L., & Chaffin, D. B. (1995). An ergonomic evaluation of handle height and load in maximal and submaximal cart pushing. *Appl Ergon, 26*(3), 173-178.

Sanborn, C. F., & Jankowski, C. M. (1994). Physiologic considerations for women in sport. *Clin Sports Med, 13*(2), 315-327.

Shoaf, C., Genaidy, A., Karwowski, W., Waters, T., & Christensen, D. (1997). Comprehensive manual handling limits for lowering, pushing, pulling and carrying activities. *Ergonomics, 40*(11), 1183-1200.

Snook, S. H. (1978). The design of manual handling tasks. *Ergonomics, 21*(12), 963-985.

Snook, S. H. (1988). Approaches to the control of back pain in industry: job design, job placement and education/training. *Occup Med, 3*(1), 45-59.

Snook, S. H., Campanelli, R. A., & Hart, J. W. (1978). A study of three preventive approaches to low back injury. *J Occup Med, 20*(7), 478-481.

Snook, S. H., & Ciriello, V. M. (1991). The design of manual handling tasks: revised tables of maximum acceptable weights and forces. *Ergonomics, 34*(9), 1197-1213.

Todd, A., I. (2005). Current Trends in Research Focused on Pushing and Pulling. *Ergonomics South Africa, 2*, 42-53.

van der Beek, A. J., & Frings-Dresen, M. H. (1995). Physical workload of lorry drivers: a comparison of four methods of transport. *Ergonomics, 38*(7), 1508-1520.

Waters, T. R., Putz-Anderson, V., Garg, A., & Fine, L. J. (1993). Revised NIOSH equation for the design and evaluation of manual lifting tasks. *Ergonomics, 36*(7), 749-776.

Winkel, J., & Mathiassen, S. E. (1994). Assessment of physical work load in epidemiologic studies: concepts, issues and operational considerations. *Ergonomics, 37*(6), 979-988.

Chapter 5 - Appendices

5.1 Equipment Technical Specifications

The following is a detailed description of the technical specifications of the equipment used for data collection. The Acupath™ Lumbar Motion Monitor™, Metamax™ portable metabolic cart, Massload® ML200 strain gage and IOtech Daqbook/2000E® analog to digital converter were all used for this research investigation.

Lumbar Motion Monitor

As indicated, the LMM™ is an exoskeleton that has three wires running the length of it. These wires are connected to three potentiometers for each direction of movement (sagittal, lateral and twisting). A change in tension on these wires (from a movement) causes a change in voltage which is then interpreted as changes in the range of motion, velocity and acceleration. The internal sampling rate is 4 MHz and there is only one channel, data from the potentiometers are sent to the PC in a single, serial data stream at a 9600 baud rate. The device is approximately 1.5 kg's and 13 x 6.5 cm's for the bottom section, 10 x 5cm's at the top section and 48 to 58 cm's in length, depending on a small, medium or large configuration. A device that is suitable for measuring trunk kinematics is the Acupath Lumbar Motion Monitor® (LMM) developed by NexGen Ergonomics. The LMM is an exoskeleton that has three wires running the length of it. These wires are connected to three potentiometers for each direction of movement (sagittal, lateral and twisting). Several research investigations have looked into the accuracy and reliability of the LMM (Gill & Callaghan, 1996; W. S. Marras, Fathallah, F.A., Miller, R.J., Davis, S.W., Mirka,G.A., , 1992; W. S. Marras et al., 1995). Marras *et* *al.* (1992) investigated the LMM compared to a standard kinematic motion analysis system and determined that it was about twice as accurate as these systems. The independent study by Gill and Callagahan (1996) aimed to build on previously published research (Marras *et al.*, 1995) that indicated the LMM was highly reproducible for measuring the range of motion (RoM), velocity and acceleration, albeit in a strictly controlled task. The aim of their study was to test the intra- and intertester reproducibility under normal movement conditions and they concluded that the LMM was found to have good reproducibility, especially with RoM and velocity measures and can be used in confidence in research and clinical settings. However they did list several limitations with their investigation of the LMM. A universal limitation that they described is due to individual variations it is difficult to place the LMM on different subjects and expect to measure the same spinal segments, as a result of this they could not test the validity of the device. Despite the limitations, the overall consensus is that the LMM does provide reliable and valid measures of thoracolumbar kinematics (reported as displacement (deg), velocity (deg•sec^{-1}) and acceleration (deg•sec^{-2})) and that these measures are important for assessing the risk factors associated with biomechanical performance of the task.

Metamax Portable Metabolic Cart

The Metamax™ portable metabolic cart was used to measure indirect calorimetry via O_2 and CO_2 gas exchange. This system is a breath-by-breath portable system (L/W/H = 12- x 110 x .45 cm's x 2) and weighs approximately 0.650kg. For data collection it contains a 16bit processor with internal sampling rate of 20 MHz and is capable of 8 MB of storage. This device is intended for use in a variety of environmental conditions: temperature range of -10° to +40°C, barometric pressure range of 500 to 1500 mbar and a humidity rating of 0-99%. The Metamax™ contains several analyzers: volume transducer with a digital turbine (0.1l/s to 12l/s, resolution of 7ml and a 2% accuracy), O_2 analyzer with an electrochemical (nafion sensor, 0-35% O_2 range, and 0.1 % accuracy) sensor, an infrared CO_2 analyzer (0-13% CO_2 range, and 0.1% accuracy) sensor, a silicon based pressure (200-1050mbar range and 1.8 % accuracy) sensor, a NTC Thermistor temperature (-55°C to 155°C, 1°C accuracy) sensor, and a POLAR® heart rate sensor. Prior to testing, gas analyzers and volume were two point calibrated with medically certified calibration gases (16%O_2 and 3.8% CO_2) and atmospheric conditions. Volume calibration was performed with a 3l calibration syringe. All gas measurements were standardized with standard temperature pressure and dry (STPD) conditions.

Strain Gage

A uniaxial load cell (Model ML200 - Massload®) was connected in serial with the pulling handle and the load. The operating temperature range for this device is -40°C to + 57°C and it is rated for a capacity of 115kg's. The total full scale relative error rate with this device is ± 0.06% (Non-Linearity <0.03%, Hysteresis <0.02% and Non-repeatability <0.01%). This device was connected via a BNC connector to a data acquisition system and three point calibrated with a series of known weights. From this an algorithm was determined and input into the analog to digital converter software.

Analog to Digital Converter

The IOtech Daqbook/2000E® has dimensions of 285 mm W x 220 mm D x 70 mm H and weighs approximately 1.7kg. It has an operating temperature range of 0° to +50°C and a humidity range of 0 to 95% (non-condensing conditions). Through successive approximation (16bit resolution, conversion time of 5 μs) data is converted from a continuous analog signal into a discrete digital signal and transformed via the algorithm into a load (kg). This device has a maximum sampling rate of 200 kHz.

5.2 Subject Experimental Equipment Setup

For data collection subjects were outfitted with a Lumbar Motion Monitor, Metamax portable metabolic system, fixed in a standardized foot position (based on anthropometrics) and instructed to pull on a handle that was connected in serial to a load (See Figure 6 and 7).

5.3 Figure Captions

Figure 3 –Example of determining the peak velocity. Each of the ten (10) successive peaks were marked at three separate intervals (two, three and eight minutes) during each ten (10) minute trunk kinematic data session.

Figure 4 – Example of trunk kinematic data overlapped with force data. The movement data was overlapped with the force data to control that each movement was appropriately paired with a pulling action.

Figure 5 – Example of a truncated oxygen consumption data file. The sections before and after the dotted lines are pre- and post- pulling sections, respectively. The section within the dotted lines was integrated and allometrically scaled as a means of comparisons within subjects.

Figure 6 – Front view of the experimental setup. The participant is equipped with a portable metabolic unit, the LMM and is holding a handle that is connected in serial to a load cell.

Figure 7 - Example of the LMM placement on the subject. The LMM is an exoskeleton that measures trunk kinematics (side bending, frontward / backward bending and trunk twisting).

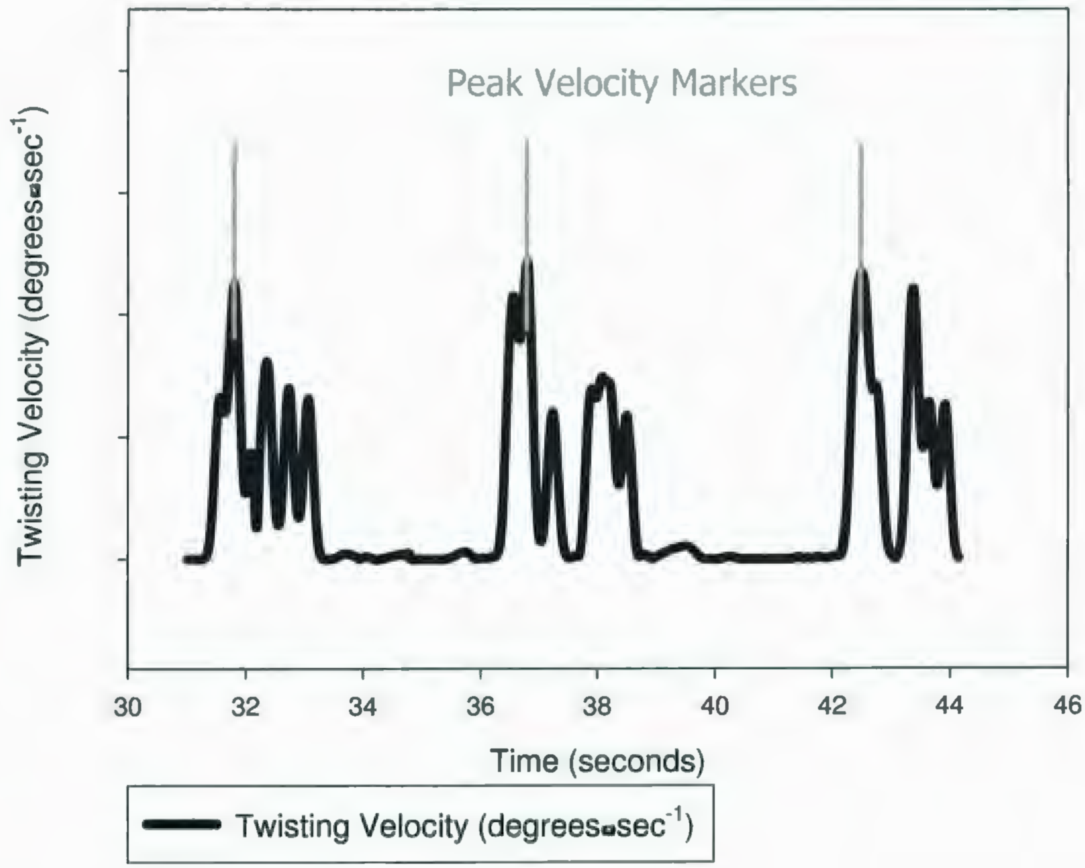

Figure 3 - Example of Marked Peak Velocity

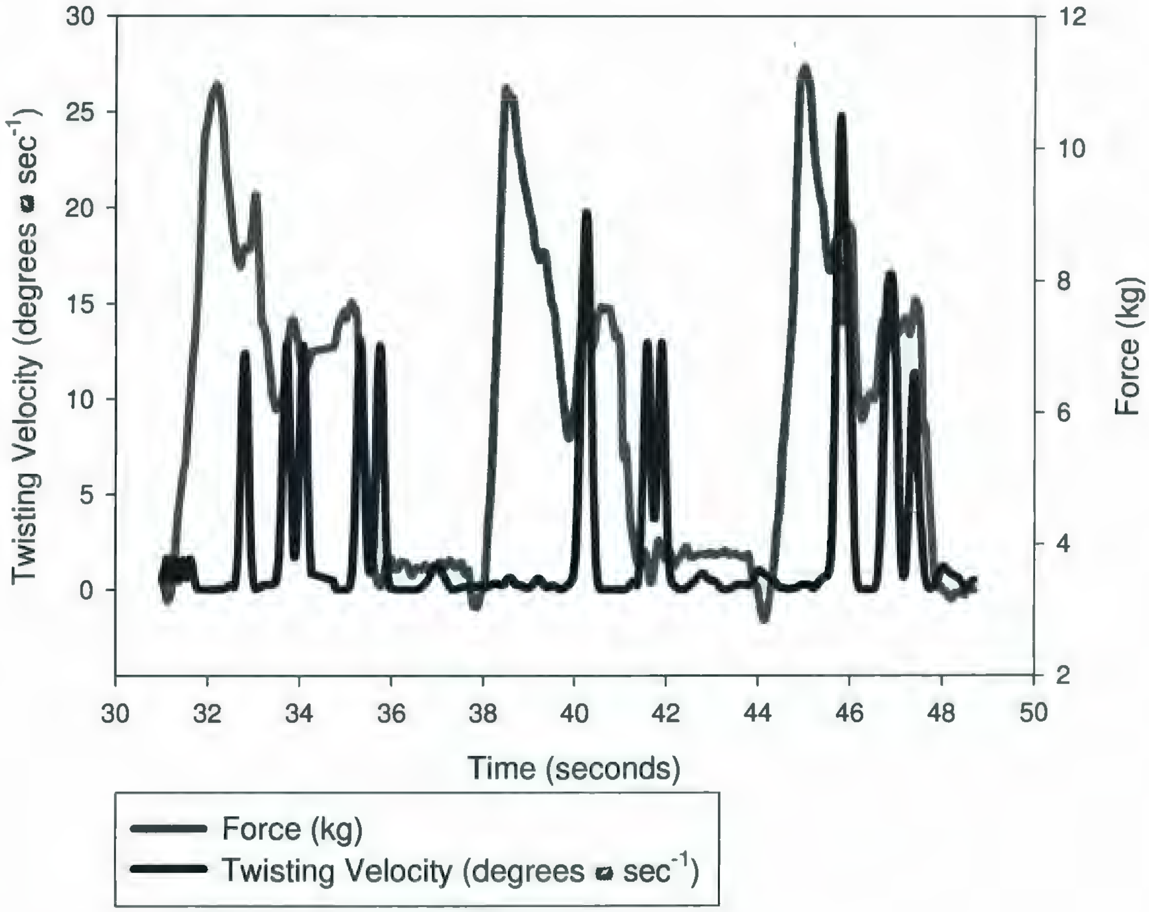

Figure 4 - Example of Force Overlapped with Trunk Kinematics

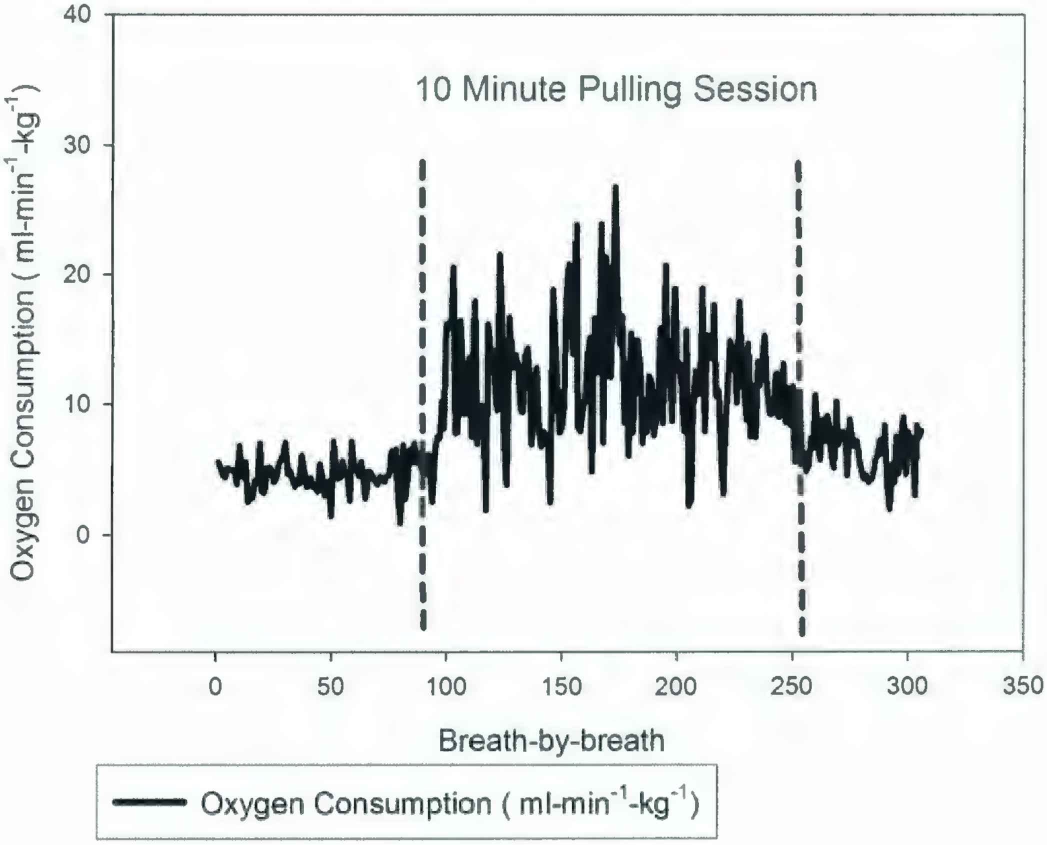

Figure 5 - Truncated Ten Minute Pulling Section

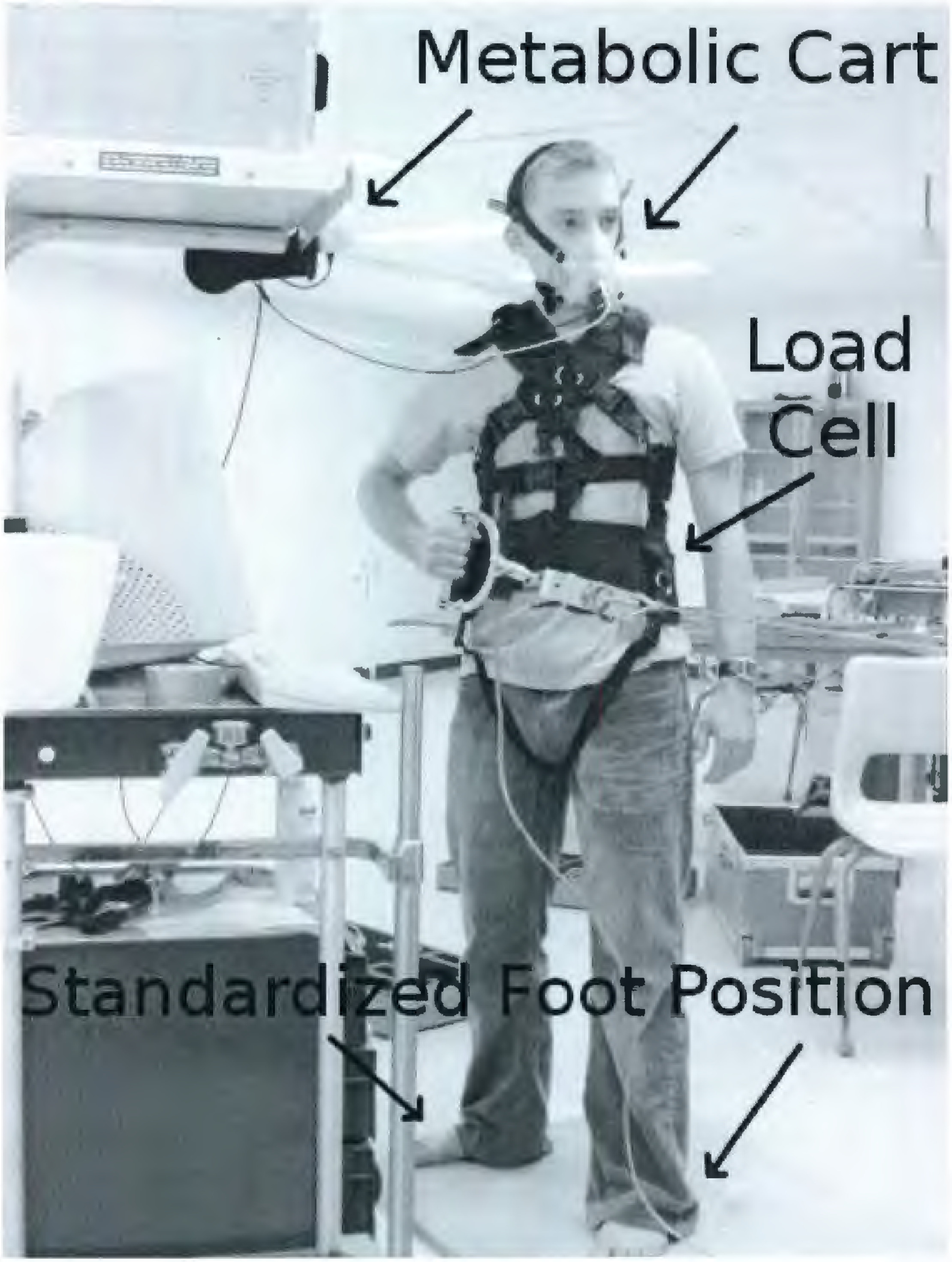

Figure 6 - Front View of Equipment Setup

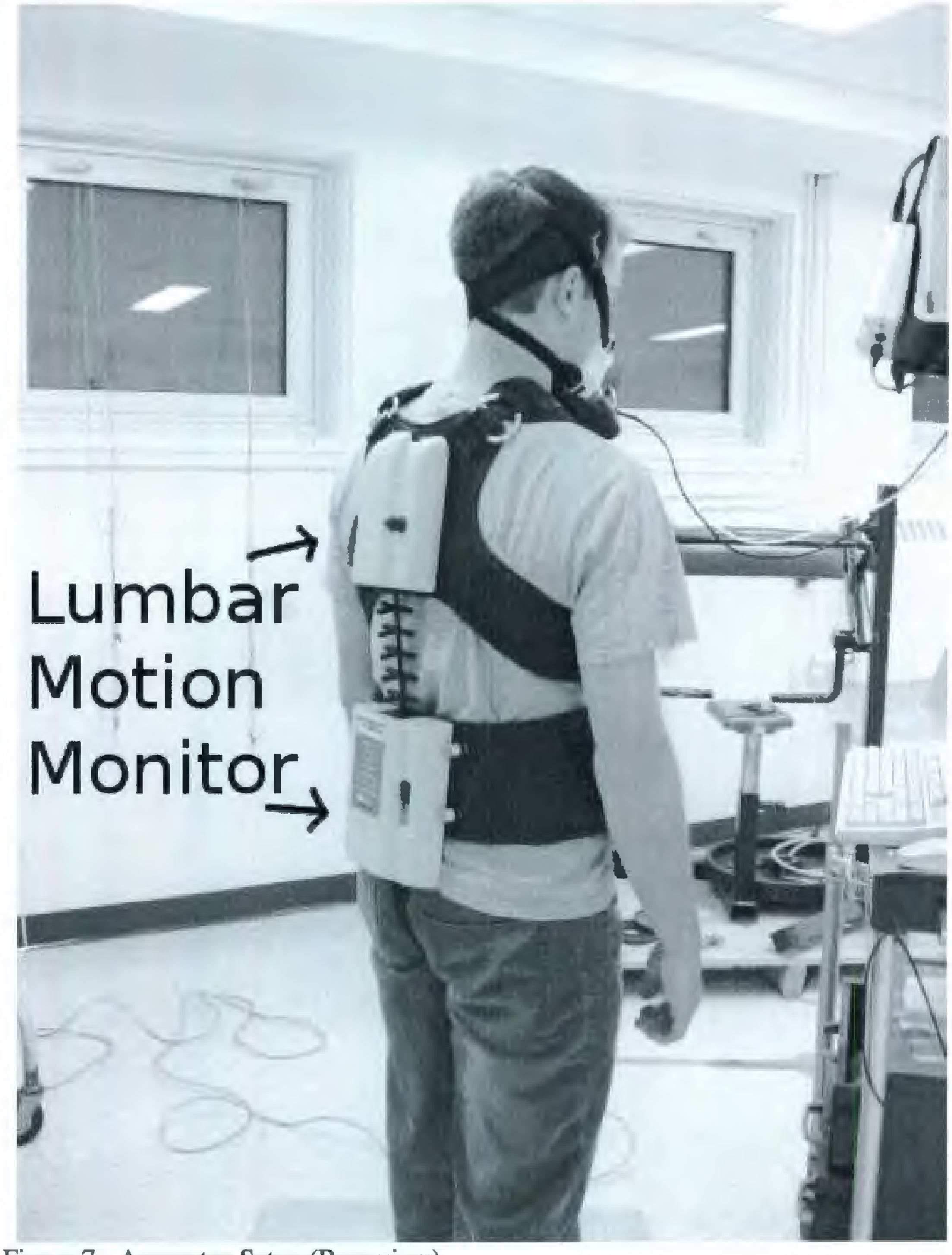

Figure 7 - Apparatus Setup (Rear view)