THE IMPACT OF LOAD AND FREQUENCY ON THE BIOMECHANICAL, PHYSIOLOGICAL AND PERCEPTUAL RESPONSES TO DYNAMIC PUSHING.

BY

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THESIS

Submitted in fulfilment of the requirements for the Degree
Master of Science

Department of Human Kinetics and Ergonomics
Rhodes University, 2006

Grahamstown, South Africa

ABSTRACT

The objective of the present research was to establish the biomechanical, physiological and perceptual responses of male operators to dynamic pushing tasks. The pushing tasks were performed using an industrial pallet jack with varying load/frequency combinations, in a controlled laboratory environment.

Thirty healthy male subjects comprised the sample. Experimental procedures were conducted utilising the Chatillon™ Dynamometer to measure force output in the initial, sustained and ending phases. The K4b^2 Ergospirometer was used to assess physiological responses (heart rate and oxygen consumption [$\dot{V}O_2$]). Nine recorded forces and nine experimental conditions formed the basis of this study, with subjects required to push three loads (200kg, 350kg, 500kg) at three frequencies (1/20 sec, 1/40 sec, 1/60 sec) at a speed of 3.6km.h^{-1} over 14 metres on a co-efficient of friction controlled walkway for six minutes. Gait analysis, along with perceptions of exertion ('Central' and 'Local' RPE) were collected during the third and sixth minutes of each condition. Body discomfort and contribution were identified upon completion of each condition.

The results demonstrated that load and frequency interacted to influence responses within each domain. Increasing loads required increased force output during each stage of the push, which had a concomitant effect on physiological and perceptual responses. Significant differences arose between the initial, sustained and ending forces for each load, showing the direct relationship between load and force exertion. The combination of heaviest load/quickest frequency required the greatest physiological output, exceeding recommended guidelines for heart rate, $\dot{V}O_2$ and energy expenditure responses. Intermediate combinations required moderate and acceptable energy cost. Linear relationships were established between heart rate and oxygen consumption, as well as between load and $\dot{V}O_2$, thus providing industrial practitioners an opportunity to evaluate task demands *in situ*. The combination of high forces and elevated physiological responses increased the subjective rating of the condition.

The results emphasise the need to holistically consider all contributing factors in a dynamic pushing task. Dynamic pushing tasks place biomechanical, physiological and perceptual demands on the human operator, which must be minimised in order to ensure that this form of manual materials handling becomes sustainable in the long term.

ACKNOWLEDGMENTS

I would like to acknowledge and thank the following people for their encouragement and support in conducting this study:

To my supervisor, Andrew Todd for invaluable input and guidance during the course of this study.

To Francois Lamont for his technical expertise as well as the time and effort spent repairing the numerous items used in this study.

To Candice Christie for her valuable expertise and input.

To my fellow Masters students, whose assistance and support was always appreciated.

To June McDougall, who came to my rescue in a time of need.

To my parents for their unconditional support throughout my University years. Without them I would never have been able to get this far.

To Katherine Thorneycroft for all her patience and support throughout the course of this thesis.

To all of my subjects who willingly gave of their time and participated enthusiastically; you helped make this project a success.

TABLE OF CONTENTS

LIST OF FIGURES

FIGURE **PAGE**

LIST OF TABLES

TABLE PAGE

CHAPTER I

INTRODUCTION

BACKGROUND TO THE STUDY

The physical demands of manual tasks such as lifting, lowering, carrying, holding, pushing and pulling pose considerable physical stresses upon the operators. This challenges their biomechanical, physiological and psychological capacities (Dempsey, 1998). A balance between work demands and worker abilities is essential to optimise work performance. Achieving the balance between these two components of work, thereby creating effective and efficient working situations, is in turn a challenge. A disturbed equilibrium at any stage can have dire consequences, resulting in cumulative or even immediate debilitating injuries (Asogwa, 1987 and Shahnavaz, 1987). In developing countries such as South Africa, worker capacity is often exceeded by the demands of the manual task. These problems are compounded by the economic situation of the country and poor education levels of workers involved in manual labour.

While technology is a significant driving factor affecting the expansion and development of independent economies, it also impacts the direction and growth of ergonomics (Bridger, 2003). In developing countries, demographic changes are imposing new constraints on organisations and there is a growing divide between skilled and unskilled workers (O'Neil, 2000). Such economies are characterised by the severe shortage of skilled workers and abundance of unskilled labourers, together with legislation requiring equal opportunities for all (South African Department of Labour, 1998), and increasing numbers of females involved in manual work. These changes in workplace dynamics and ethnic construct have meant the redesign of work stations, in order to ensure that the majority of workers are not physically over taxed. IDCs can seldom afford the complex modern technology used in Industrially

Advanced Countries (IACs); hence there is a tendency to exploit manual labour willing to work any job for minimal wages.

Chavalitsakulchai and Shahnavaz (1993) found an urgent need for ergonomic intervention in IDCs using low-cost improvements and appropriate training methods, but they also emphasised the need for research given the specific characteristics of the IDC. This weakness in ergonomics was acknowledged by Hendrick (1994), who stated that the current application of ergonomic knowledge and intervention strategies does not benefit more than half the world's population. In many developing countries, such as South Africa, these statements remain valid 13 years later. South Africa is characterised by and recognised internationally for its diversity of culture and ethnic groups, thus creating a further challenge to ergonomists aiming to optimise any working environment. Taking cognisance of this challenge is important in successfully introducing effective and efficient ergonomic practices. Kogi and Kawakami (1997) have however argued that there is a growing recognition in developed and developing countries that simple improvements to prevent musculoskeletal disorders have multiple impacts on safety and productivity. Therefore, in order to make ergonomics viable within IDCs, the concepts and solutions must search for innovative and low cost means of implementation. Scott and Charteris (2001) reiterate the need for ergonomics in developing countries as they emphasise the inverse relationship between ergonomic need and ergonomic supply, whereby the people most in need of ergonomic input are those who are not gaining from it; hence a continued incompatibility between worker and task.

Manual handling research has historically focused on lifting and carrying, as these two tasks are predominant in industry. These tasks inherently predispose workers to high levels of physical stress, which manifests as cardiovascular and musculoskeletal strain. In an attempt to reduce injuries associated with MMH, the replacement of the lifting component with the use of industrial carts has seen the rise of repetitive pushing and pulling tasks in industry (Resnick and Chaffin, 1995; Hoozemans **et al.**, 1998; Al-Eisawi **et al.**, 1999; Ciriello, 2004). Push/pull tasks seem more acceptable to the majority of the workforce due to the apparent attraction of being able to move greater loads at a reduced physical cost to the operator. Straker **et al.** (1996) found the physical limits for pushing and pulling to be double those of lifting, with concomitantly lower subjective ratings. However, Resnick and Chaffin (1995) warn that these changes create a new set of demands, as yet not fully quantified, to which the individual's musculature and cardiovascular systems must adapt and cope. In 1981 NIOSH reported that as many as 20% of all injury claims could have been attributed to pushing and pulling efforts. Since then, many authors (Hoozemans **et al.**, 1998; Granata and Bennet, 2005) have substantiated this value, and it is expected that this injury rate will increase in response to the trend toward a growing number of push-related tasks in the workplace. Lee **et al.** (1991) observed that many overexertion injuries, particularly to the lower back, were recognised as being caused by pushing and pulling tasks. Unfortunately limited research exists exploring the relationship between pushing and pulling work and other musculoskeletal disorders (Hoozemans **et al.**, 2004), although evidence does suggest a relationship with shoulder complaints (de Looze **et al.**, 2000; Schibye **et al.**, 2001; Laursen and Schibye, 2002; Hoozemans **et al.**, 2002; Kingma **et al.**, 2003).

De Looze **et al.** (2000) and Jansen **et al.** (2002) argued that despite increased awareness and acknowledgment of pushing and pulling as a form of manual work, and the associated high injury costs, pushing and pulling has received little scientific attention. Differences in methodology, sample characteristics and acceptable force criteria have led to conflicting data on pushing and pulling capabilities (Daams, 1993; Al-Eisawi **et al.**, 1999; MacKinnon 2002). Current literature lacks consensus and clarity regarding the implications of the dynamic nature of push/pull tasks, the slip potential, human behaviour and perception, and changes in muscle activity, posture and performance capability (Ferreira **et al.**, 2004). Epidemiological knowledge of the relationship between pushing and pulling and musculoskeletal complaints is sparse, and the role of task factors such as frequency and load, as well as the impact of the interaction of these on physiological cost are even less well documented.

Research to date is not clear as to which of pushing and pulling actions are most appropriate or desirable from either a biomechanical, physiological or psychophysical perspective. Depending on the methodology employed, differing and inconsistent results have been attained. Several studies have suggested that from a biomechanical perspective it is better to push than to pull (Lee **et al.**, 1991; Laursen and Schibye 2002), yet there is no evidence from a physiological perspective to support this (Todd, 2005). The focus of this current research will thus be on the holistic demands placed on individuals during dynamic pushing tasks, as witnessed in industry, investigating the role of load and frequency in determining the demands placed on the human operator.

STATEMENT OF THE PROBLEM

Despite the recognition that dynamic pushing tasks are becoming more prevalent, very few studies have taken a holistic integrated approach to assessing demands placed on the human under such conditions. In any pushing activity, the interaction between load and frequency plays a critical role in determining the physical and mental workload to which the operator is exposed. Quantification of the biomechanical, physiological and psychophysical workload regardless of context (IAC or IDC) is critical for work optimisation.

This study aims to assess an individual's biomechanical, physiological and perceptual responses to dynamic pushing activities, simulating conditions evident *in situ.* The findings will enable a better understanding of demands of repetitive pushing tasks. This will be achieved primarily through optimisation of load and frequency due to the impact these two variables have on force production during the initial, sustained and ending phases of a pushing task. Coupled with the Manual Handling Devices (MHD) design, consideration of these factors is crucial in order to prevent physical overexertion and also to limit the physiological cost experienced by the body. Postural changes that result in an increased risk of slip, trip and fall (STF) and musculoskeletal injury due to load and task intensity can be identified, and where need be, corrective measures introduced in order to prevent the long term occurrence of injury.

RESEARCH HYPOTHESIS

The objective of this research is to examine the biomechanical, physiological and psychophysical responses of male operators to changes in load and load/frequency combinations during dynamic pushing tasks. The research aims to identify load/frequency combinations at which all responses are optimised. It is proposed that increases in load are expected to increase the biomechanical demands during the initial, sustained and ending phases of the dynamic pushing task. It is further proposed that an increase in load and/or frequency will increase the physiological and perceptual demands of the task.

STATISTICAL HYPOTHESIS

Biomechanical Hypotheses

Hypothesis 1 (a): The biomechanical forces (N) exerted during the initial (i), sustained (s) and ending (e) phases of the dynamic push task are equal for all loads.

H_o: $\mu_{F\,200kg} = \mu_{F\,350kg} = \mu_{F\,500kg}$

H_a: $\mu_{F\,200kg} \neq \mu_{F\,350kg} \neq \mu_{F\,500kg}$

F = initial; sustained and ending forces.

Hypothesis 1 (b): The forces (N) exerted at each load (200kg, 350kg and 500kg) are equal.

H_o: $\mu_{iL} = \mu_{sL} = \mu_{eL}$

H_a: $\mu_{iL} \neq \mu_{sL} \neq \mu_{eL}$

L = 200kg, 350kg and 500kg load.

Hypothesis 1 (c): Gait pattern responses (stride length and cadence) are equal for all load/frequency combinations.

H_o: $\mu_{\text{Gait 1}} = \mu_{\text{Gait 2}} = \ldots\ldots \mu_{\text{Gait 9}}$

H_a: $\mu_{\text{Gait 1}} \neq \mu_{\text{Gait 2}} \neq \ldots\ldots \mu_{\text{Gait}}$

1, 2...9 represent the nine conditions created through load and frequency.

Physiological hypothesis

Hypothesis 2: The physiological responses (Heart Rate, Oxygen consumption [$\dot{V}O_2$], Energy Expenditure) during all load/frequency combinations are equal.

H_o: $\mu_{\text{Phys 1}} = \mu_{\text{Phys 2}} = \ldots\ldots \mu_{\text{Phys 9}}$

H_a: $\mu_{\text{Phys 1}} \neq \mu_{\text{Phys 2}} \neq \ldots\ldots \mu_{\text{Phys 9}}$

1, 2...9 represent the nine conditions created through load and frequency.

Psychophysical hypothesis

Hypothesis 3: The perceptual responses (RPE) to all load/frequency combinations are equal.

H_o: $\mu_{\text{RPE 1}} = \mu_{\text{RPE 2}} = \ldots\ldots \mu_{\text{RPE 9}}$

H_a: $\mu_{\text{RPE 1}} \neq \mu_{\text{RPE 2}} \neq \ldots\ldots \mu_{\text{RPE 9}}$

1, 2...9 represent the nine conditions created through load and frequency.

DELIMITATIONS

This study aimed to investigate the impact of load on an individual's biomechanical force output in the initial, sustained and ending phases of a pushing task, as well as the subsequent impact of nine load/frequency combinations on an individual's physiological and perceptual responses. A sample of 30 male subjects aged between 18 and 26 drawn from the general population volunteered to participate in this study. Self report clarified that no subject had a history of musculoskeletal problems and all were free from any current injury. The testing procedures were confined to a laboratory where the influence of environmental factors, particularly light and heat was minimised.

Subjects who agreed to participate in the study were given a letter of information outlining the basic aims, requirements and procedures of the study. All subjects signed informed consent before participating. Subjects were allocated codes which corresponded to a particular random sequence of conditions. Experimentation took place in sessions of 60 minutes, attended by two subjects per session. Each session involved performing three conditions, each over a six-minute period. The first time a subject pushed each of the three loads, they performed two trials, during which the exerted forces were measured, before continuing with the six-minute condition. Biomechanical, cardiorespiratory, metabolic and perceptual responses were monitored during each condition.

LIMITATIONS

Despite the researcher's best efforts, the network causality of all the individual factors (such as biomechanical, physiological and perceptual) renders it impossible to control for all eventualities. However, every effort was made to ensure rigorous control of as many extraneous factors as possible.

The following limitations remained and should be taken into consideration when examining the results.

1. Subjects were student volunteers, and were thus self motivated to perform optimally, although researchers made every effort possible to motivate the subjects throughout the study. In addition, all attempts were made to choose as diverse an ethnic representation as possible; however, subjects' demographics did not match the South African population.
2. Besides the requested dietary compliance, subjects followed normal eating, drinking and exercise habits during the course of the study, with no researcher control over these external factors.

3. Clear and detailed instructions were given on the use and interpretation of the perceptual scales; however, “self reports” continue to be problematic, and the validity of these results must be appraised with this consideration.

CHAPTER II

REVIEW OF RELATED LITERATURE

INTRODUCTION

Technology continues to drive the production processes of most industries in Industrially Advanced Countries (IACs). However, in Industrially Developing Countries (IDCs), this technology is frequently inaccessible and expensive, with income derived mainly from agricultural activities requiring little or no technology (Shahnavaz, 1996). IDCs are characterised by low levels of education among a large proportion of the workforce (Sen, 1984). Such problems contribute to physical work dominating in these sectors of the population, traditionally associated with poor wages, resulting in low standards of living and elevated population growth, leading to high levels of unemployment and low productivity.

Internationally, men and women are involved in Manual Materials Handling (MMH), particularly in IDCs, which comprise as much as three quarters of the world's working population (Scott, 1999). Frequently, the requirements of the task exceed the abilities of the person responsible for its execution, resulting in an incompatibility which can ultimately lead to overexertion injuries, particularly musculoskeletal (Ayoub and Mital, 1989). Marras **et al.** (2000) argued that despite advances in technology, the rate of workers' compensation claims have not been reduced, even for lower back injuries. Shoaf **et al.** (1997) described how injuries related to manual work were primarily caused by overexertion, with 61% of the injuries related to the lower back. These authors go on to argue that approximately 15% of these injuries were attributed to pushing and pulling, while Hoozemans **et al.** (1998) contend that the increasing number of musculoskeletal complaints relating to individuals' upper extremities are possibly a result of the change in task requirements in industry. Ergonomists strive to achieve optimisation of the interaction between workers and their work environment or task (Bridger, 2003), thereby boosting efficiency, reliability and ultimately, productivity.

ERGONOMICS IN INDUSTRIALLY DEVELOPING COUNTRIES

Shahnavaz (2000) and O'Neill (2000) reported that the world's working population in developing countries is engaged primarily in agriculture or small-scale enterprises. In South Africa, the vast majority of the working population is involved in mining, forestry, general industry or agriculture. Workers in IDCs face a unique array of problems compared to those in more developed nations. Jafry and O'Neill (2000) propose that a country's development is driven by three elements: economic, social and human, which interact to bring about change. Although striving for overall improvement in quality of life, primarily through economic growth, the hasty rate of change is frequently too quick to suit the individuals or the society, thereby creating new problems, with the majority of the populace being ill-equipped to deal with them (Shahnavaz, 1987). In addition to economies which characteristically struggle to compete internationally, or even provide minimal assistance to rural/subsistence labourers, IDCs rely extensively on human energy for the necessary power to carry out work tasks (Jafry and O'Neill, 2000). Further, high population growth leads to extreme unemployment problems, which exacerbate the poverty problem. With a large semi-illiterate population surviving below the poverty line, the poor quality of life ultimately develops into a negative spiral, which increases the potential for accidents and occupational diseases (Shahnavaz, 1987; O'Neill, 2000).

Ergonomics, as the scientific discipline concerned with human interactions within a system, is the developing science best equipped to examine and deal with the range of problems apparent in developing countries (O'Neill, 2000). Ergonomics in IDCs is still an emerging application (Bao and Shahnavaz, 1989; O'Neill, 2005), even amongst the more commercialised communities, and the institution of its principles in IDCs differs from that traditionally followed in IACs (Sen, 1984). A grassroots approach has the opportunity to impact on the largest majority of actively working individuals, and hence has potential to generate a positive turn around, in both the community and country's fortunes. This approach has been advocated by Kogi (1998), who believed ergonomic concepts are best described from the perspective of local interpretation and application, hence providing the greatest influence, physically and economically, from the bottom up.

Heavy manual labour has dominated much of the workers' activities in IDCs, and continues to do so, as the labour force is widely regarded as expendable (O'Neill, 2000), a problem further aggravated by unemployment. Work processes which require harmful working methods, such as unnatural postures and repetitive actions, coupled with poor environmental conditions, such as pollution and heat, are the cause of many accidents and subsequent low productivity (Shahnavaz, 1987). Bao and Shahnavaz (1989) argued that only by identifying the local needs, considering the local problems, setting feasible objectives and utilising the available resources can the potential benefit of ergonomics be properly used to solve the problems in IDCs.

Jafry and O'Neill (2000) stated that the multi-disciplinary nature of ergonomics can play a unique role in the protection of people's health and in the prevention of work-related health hazards. This is achieved through integrating concepts from social sciences with technological advances to enhance productivity. Holistic in nature, elements relating to biomechanical, physiological, psychological, social and cultural elements can be correctly identified and effectively treated in ergonomic interventions. Justification for ergonomic intervention based on physical benefits is no more apparent than in the design of work methods, equipment and environments to suit the capacities of users, hence greatly improving their performance, comfort and health (Beevis and Slade, 2003). Poor working conditions and the absence of effective work injury prevention programmes in IDCs has resulted in very high rates of musculoskeletal disorders (MSDs) (Shahnavaz, 1987). Common disorders include back and neck ache, primarily attributable to working in inefficiently organised work space, bearing heavy loads and badly aligned working postures. These injuries are recognised as potentially disabling, and can translate into absenteeism and loss of income causing disruption to life (Jafry and O'Neill, 2000).

MANUAL MATERIALS HANDLING

Manual Materials Handling (MMH) tasks are a significant cause of compensable injuries, and the economic consequences of handling materials manually are far from trivial (Dempsey, 1998). In fact, manual work has been widely shown to be the most expensive category of compensable loss (Leamon and Murphy, 1994), and Webster and Snook (1994) report that in many countries workers' compensation costs for injuries relating directly to occupational requirements can run into billions of dollars each year. Therefore, establishing means of controlling injuries directly linked to manual labour can be of considerable economic benefit to employers, employees and society in general. Ayoub and Mital (1989) suggested that the prevention and control of occupational injuries can be achieved through the establishment of acceptable working limits, through the application of ergonomic principles in design, training and employee selection. Research is now being directed towards redesigning work stations and work environments of high risk manual jobs in order to accommodate the highest percentage of both the male and female populations (Snook, 1987) in order to reduce the likelihood of disability.

In order to reduce the inherent stresses of manual labour, the ratio of task demand to worker capacity must be carefully controlled. Taylor (1911) was the first to document that keeping task demands within the acceptable physical capabilities of the worker can have a positive effect on productivity. To control task demands, activities which manifest as musculoskeletal and cardiovascular strains, resulting in fatigue and discomfort, must be eliminated or reduced wherever possible (Dempsey, 1998). General research has continued on lifting tasks, despite the contention by Baril-Gingras and Lortie (1995) as well as Hoozemans **et al.** (1998) that many MMH tasks require operators to exert repetitive submaximal pushing and pulling forces, predisposing them to a strong possibility of injury. Since the extensive studies into lifting and its influences on worker capabilities and resulting musculoskeletal problems, Resnick and Chaffin (1995) explain that work processes and task designs have been altered, with designers eliminating lifting jobs and implementing carts and manual handling devices, resulting in an increased prevalence of repetitive pushing and pulling tasks. This has meant that up to 50% of industrial MMH tasks are now completed through pushing and/or pulling (Kumar **et al.**, 1995; Baril-Gingras and Lortie, 1995), which Straker **et al.** (1997) report as being subjectively rated as less taxing than lifting.

Field investigations vs. Laboratory research

Despite much debate and possible controversy, the question still remains whether experimental results obtained in controlled laboratory environments are comparable to *in situ* investigations. Both field and laboratory investigations have their respective advantages and disadvantages, making the issue a difficult one to solve.

Oborne (1995) stated that the main drawback of conducting research in the field is that experimental conditions are less rigorously controlled than in the laboratory, due to the countless extraneous factors which are beyond control. In the laboratory, working situations can be artificially reconstructed, allowing all experimental conditions and treatments to be controlled, thereby isolating the true responses to the task. However, this 'cold' controlled environment puts the validity of the findings to external locations into question, possibly rendering the findings unreliable and solutions ineffective. Investing time and money into unusable solutions could be disastrous for management, and so all laboratory-devised interventions must be thoroughly tested for compatibility with the real working environment. Conversely, collecting data in industrial settings is wrought with problems such as disrupting the production or work process, as well as being expensive and time consuming, and many of the subjects' responses may be 'tainted' by psycho-social issues that influence responses. The mere presence of researchers may provoke 'unnatural' or unusual responses, thereby nullifying the investigation.

Bao and Shahnavaz (1989) state that ergonomics is an applied science which requires that research, thus far limited to academic fields, be taken out and applied in field situations. Pushing and pulling investigations, in a relatively early stage, still require the sound theoretical laboratory research before they can be confidently applied by ergonomists in everyday working situations around the world.

Gender Research

Limited literature exists regarding female manual operators, possibly due to a preconceived notion that manual work is exclusively the male domain. In IDCs, however, the poor economy has dictated that increased numbers of females are involved in hands-on labour. Research by Chavalitsakulchai and Shahnavaz (1993) into female workers in IDCs showed that "about 50% of the female workers experienced high prevalence of musculoskeletal symptoms", particularly of the upper extremity. Primary causes of the symptoms were heavy manual handling and highly repetitive and monotonous movements. Females are often required to manipulate and handle loads considered 'acceptable' for male populations, therefore placing substantial strain on their bodies and predisposing them to debilitating injuries.

Characteristics and capabilities of individuals differ substantially, and sex-related differences are commonly used as reasons for preventing females from taking part in manual work. Despite this, the economic situation within IDCs, and social pressure in IACs, has meant that women are becoming increasingly engaged in physically demanding tasks. The increase of female operators in industry, tackling tasks previously dominated by males, has increased the diversity of members of the workforce (Knapik, 1997). It is well documented that there are gender differences with respect to body weight and height, as well as relevant personal factors such as muscular and energy capacity (van der Beek **et al.**, 2000). Previous research into gender disparity in pushing and pulling tasks has tended to focus on the psychophysical component. Ten psychophysical studies were reviewed by Hoozemans **et al.** (1998), and confirmed the need to recognise the sex-related differences in absolute muscular strength: that men are capable of exerting greater maximum pushing and pulling forces. The subjects involved, however, differed too in anthropometric characteristics, with the men being heavier and taller on average. Anthropometric differences were shown by Ayoub and McDaniel (1974) to affect pushing and pulling strength, with an increase in body weight accompanied by an increase in push/pull strength. Sharp **et al.** (1993) highlighted that females are at a distinct disadvantage regarding manual work, because their overall absolute strength is approximately 63% that of males. Shepard (2000) concurred with this finding, and concluded that females have naturally reduced aerobic power and less muscle mass than males, due particularly to body mass, hormonal differences and socio-cultural influences. Fothergill **et al.** (1991 and 1996), however, found no significant differences between the sexes when correlating lifting strength to stature and normalised body mass. The authors drew the critical conclusion that separate load limits for men and women in manual handling should not be derived from a single mean ratio, predicting female strength from male data. This was reiterated by van der Beek **et al.** (2000), who argued that due to anthropometric and physiological differences associated with gender, the physical workload of females might be proportionately higher than the workload of the males when the same tasks have to be fulfilled.

Anthropometric Considerations

Anthropometry describes the physique of an individual and is thus considered an indicator of that person's physical capacity (Floyd and Thompson, 1998). It is vital that ergonomists have a clear understanding of the relationship between the demands of the task and the individual performing the task, in order to prevent a 'mismatch' between them. Botha and Bridger (1998) and Grandjean (1986) cautioned that careful evaluation of anthropometric data is critical in the design of any workstation, in order to prevent operators assuming constrained postures. Ayoub and Mital (1989) acknowledged that stature is a key characteristic to consider, together with body size, as these factors are known to influence strength expression. Anthropometric variations between individuals can result in differences in the work produced by the individuals moving identical external loads (Adrian and Cooper, 1996). Therefore, the natural variation of human populations has implications for the design of products and tasks. Pheasant (1995) stated that sex-related differences associated with anthropometric dimensions and proportions are almost entirely biological. Pheasant (1995) further contended that males will exceed females in all linear body dimensions except hip breadth. This is important when considering workstation layout and the design of MHDs that will be operated by female workers, as any task designed to accommodate the male operator will place the female operator in that task under undue strain.

PUSHING AND PULLING

Introduction

Hoozemans **et al.** (1998) defined pushing and pulling tasks as the application of force (usually by the hands) by someone on an object or another person, provided that the largest component of the resultant force is directed horizontally. In pushing, the force is directed away from the body, and in pulling the force is directed towards the body. Pulling is characterised by the grasping of the object to be moved, whereas it is possible to exert push forces without taking hold of the object with the fingers. Commonly seen in activities of everyday life, as well as within the sporting or industrial settings, pushing and pulling is a means of manipulating objects from one area to the next (Luttgens and Hamilton, 1997). In industry, pushing and pulling can vary from moving carts and trolleys (Chaffin **et al.**, 1991; Hoozemans **et al.**, 2004) to dustbins (Laursen and Schibye, 2002) to boxes or crates (Gagnon **et al.**, 1992) or to delivery trays (Jansen **et al.**, 2002).

Epidemiology

Imrhan (1999) identified the maximum strength of pushing and pulling as the maximum force that an individual can generate at the interface of the body and the object. Many industrial activities are carried out through the application of human strength, and it is therefore a critical variable to be considered by ergonomists in the design of tasks, processes and mechanical devices. Pushing and pulling in industry is characterised by a wide variety of possible combinations. Workers can either push or pull, and they can either use one or both hands, in symmetrical or asymmetrical postures (van der Beek **et al.**, 1999). Daams (1993) further emphasised that pushing and pulling can be performed stooping or squatting; sitting or standing. Further complications include differing levels of intensity, frequency and duration, as each work situation has its own dimensions. The magnitude of strain experienced by workers involved in pushing and pulling is therefore dependent upon the characteristics of the task, such as intensity, direction and point of application; as well as frequency and duration of the activity (Hoozemans **et al.**, 1998). These external factors must be coupled with the internal responses experienced by each individual. Therefore, comprehensive force measurements and posture analysis are essential, particularly as the working technique is likely to differ between individuals (van der Beek **et al.**, 1999).

Research into lifting has resulted in an elevated awareness that lifting and carrying are major sources of injury. Work design has shifted toward a greater reliance on manual handling aids (Schibye **et al.**, 1997; Haslam **et al.**, 2002). Researchers interested in MMH began to notice and record the change in work patterns and task requirements in the early 1990s (e.g. Resnick and Woldstad, 1994; Resnick and Chaffin, 1995). Resnick, Chaffin and other colleagues began to document the rapid increase in the industrial use of material handling devices. The use of carts, trolleys, hoists and arms became more prevalent as the desire to eliminate the problems associated with lifting became paramount. Lifting and carrying were replaced wherever possible by a means of mechanical manipulation through some type of assist device (Resnick and Woldstad, 1994; Resnick and Chaffin, 1995). While device designs vary widely depending upon the application, all have one basic goal: to reduce the musculoskeletal stress on the worker by eliminating the need to support the load during manual operations (Resnick and Woldstad, 1994). This job redesign has not necessarily reduced the musculoskeletal strain associated with the task, it has merely minimised the need for lifting and carrying, and introduced substantially more pushing and pulling activities (Al-Eisawi **et al.**, 1999) with their concomitant problems.

Despite the reduced lifting component in any MMH task that now utilises MHDs, these devices still require the horizontal transfer of the load, and thus involve pushing and pulling actions. This redesign fundamentally alters the operator exerted forces, and hence the biomechanical stress on the body. Design and appropriate use of MHDs is increasingly crucial as the manipulation of the load now includes the inertia of these load assist devices and any frictional resistance effects associated with them (Resnick, 1993).

BIOMECHANICS OF PUSHING AND PULLING

The primary goal of the biomechanical approach to ergonomics is to design tasks which do not exceed the capacity of the musculoskeletal system (Dempsey, 1998). Low-back and shoulder girdle pain are major problems in the industrial sectors of any economy. Researchers have found back pain to be more prevalent among workers who have had to adopt unusual body positions or which involved trunk flexion and twisting of the spine (Keyserling **et al.**, 1988). The aetiology of musculoskeletal problems involves numerous factors, and it is universally acknowledged that pain can be caused or exacerbated by excessive loading of the joints and muscles. This loading may result from a single traumatic event or from sustained exposure to particular working postures (Marras, 2000).

Biomechanical modelling can be used to predict the stresses on the musculoskeletal system, by representing simple human models based on the anatomical structure. Using this technique, Hoozemans **et al.** (1998) identified pushing and pulling as risk factors for musculoskeletal disorders. Kumar (1990) showed that once mechanical stress exceeds the load bearing capacity of structures involved, damage may occur and joint or muscle disorders are likely to develop. Hoozemans **et al.** (1998) further concluded that despite the attention that has been given to mechanical loading of the lower back during pushing and pulling, knowledge of the mechanical load on the upper extremities is lacking. There are indications, however, that mechanical load on the upper extremities is minimised if the pushing and pulling force is exerted in a mechanically favourable direction. The relationship between exerted push and pull forces and musculoskeletal complaints has not been widely investigated, and researchers have tentatively explained that it appears "plausible that an increase in exerted forces will eventually increase the risk of MSD" (Hoozemans **et al.**, 1998).

Chaffin **et al.** (1983) and Lee **et al.** (1991) identified the interactions of handle height, foot distance, anthropometry, posture and body weight as factors influencing biomechanical loading on the body during pushing and pulling. Hoozemans **et al.** (1998) concurred when stating that pushing and pulling in the workplace has a number of factors which increase the potential risk of lower back and shoulder complaints, and highlighted that amongst these, direction of exerted force, one- or two-handed pushing or pulling, load and handle height are the most studied.

Force Output

Strength is a vital prerequisite of efficient performance in all activities of daily living, including sport and occupational tasks (McArdle **et al.**, 2001). Strength is defined as the ability to exert tension against a given resistance (Kroemer, 1970), and is influenced by a range of factors including age, sex, training status, motivation levels and health status (Charteris and Scott, 1997). Human muscular strength exertion capability is one of the most critical and basic human physical capabilities required in designing work or evaluating task effectiveness (Mital **et al.**, 1995). Weisman **et al.** (1992) argued that developing methods for measuring and matching the physical abilities of workers and the physical requirements of job tasks can help prevent injuries and improve the "return-to-work" rate of injured workers. Human strength assessment, be it upper or lower extremity, is then fundamental to understanding human performance potential under different conditions (Brown and Weir, 2001). Drury (1986) stated that when evaluating human strength capabilities, care must be taken to ensure standardisation of the biomechanical testing conditions, in order to achieve uniformity and a reliable comparison base. This is particularly important with pushing and pulling tasks, as the range of possible postures, and the variety of methodological stipulations result in a wide array of possible testing conditions.

In this light, studies of pushing and pulling have tended to focus on strength aspects of the shoulder joint, as well as attempting to establish guidelines for maximum acceptable limits for push/pull tasks, primarily from a psychophysical perspective (Snook, 1978; Ciriello **et al.**, 1993). However, since pushing-pulling activities include most body segments, each one is likely to play a role in determining the individual's overall strength magnitude capabilities (Kumar, 1995).

Chaffin **et al.** (1983) stated that individuals with a large reach and body mass have the ability to achieve high pushing and pulling forces. This is further improved with surfaces that have improved coefficient of friction and which prevent slip accidents. Daams (1993) emphasises the importance of adaptability within work environments, particularly since muscle strength is not always enhanced with increases in body mass. Larger individuals are often considerably more restricted, with limited manoeuvrability, due to body size. Thus, a larger person cannot always adopt an optimal position, in order to exploit the additional body mass to exert greater forces. Daams (1993) further recommends that knowledge of the forces exerted by future users of a product is of vital importance in the design process. The majority of users should be able to operate the product, which must in turn be able to withstand forces exerted by the strongest users.

Dynamic vs. Static Force

Isometric strength testing facilitates the determination of an individual's static push-pull exertion strength, through the use of dynamometers. For ergonomists, isometric muscle tests are relatively easy to execute, and the mechanics rather simple. However, most work activities, including MMH, are dynamic in nature, and so pure isometric work tasks are rare. Therefore these tests may lack applicability to real working situations. Kroemer (1970) explained extensively that strength data obtained from an experimental group would be adequate to describe the maximal isometric forces that can be exerted by the corresponding operator group.

Lee **et al.** (1991) categorised pushing and pulling tasks into separate static and dynamic activities. Although pushing is primarily a dynamic action, the loads to be moved are almost always stationary to begin with, and hence the initial forces exerted are predominantly static in nature. Once moving, however, the static forces are not removed, as significant movement only tends to occur in the legs and lower extremity, while the upper extremity tends to maintain a static posture while controlling and applying the necessary force onto the MHD. The static work effort is characterised by contraction of muscles over extended periods of time, most commonly in order to maintain a working posture or control over an object (such as a trolley). Static work endurance is affected by work load, and should therefore be avoided where possible (Mital and Pennathur, 1999).

Initial, Sustained and Ending Forces in Dynamic Pushing

Hoozemans **et al.** (1998) and van der Beek **et al.** (1999) stated that any pushing or pulling risk evaluation should be aimed at the assessment of exerted hand forces, as increasing hand forces are accompanied by an elevated mechanical stress on the musculoskeletal system, in particular the shoulders and lower back. Ciriello and Snook (1983) had previously proposed that dynamic pushing and pulling motions can be divided into movements executed by accelerating an object from rest (initial force), or those sustaining a moving object's motion (sustained force) through periodic accelerations or decelerations due to changes in flooring, slope and poor housekeeping. In addition to these commonly accepted forces involved in push/pull tasks, Ferreira **et al.** (2004) proposed the use of the term 'restraining force' to incorporate the maximum dynamic force required to bring an object back to rest. However, the term 'ending' force may be more appropriately used to indicate the force used to stop an object in motion, as 'restraining' force does not imply the object coming to a complete halt. This force is critical, as the required effort to stop an object already in motion can differ dramatically from either the initial or sustained forces, and thus could present a different type of risk to the operator. As yet, this component of a task has received little attention in the literature.

No pushing or pulling task is performed in isolation, as any task that requires an object to be pushed or pulled from one location to another does in fact require the opposite forces as well. Therefore in order to stop a MHD which is being pushed requires the operator to perform a pulling action. The ending phase of any push exertion is therefore actually a pulling action. Figure 1 indicates the change in direction and force exertion during the course of a pushing task.

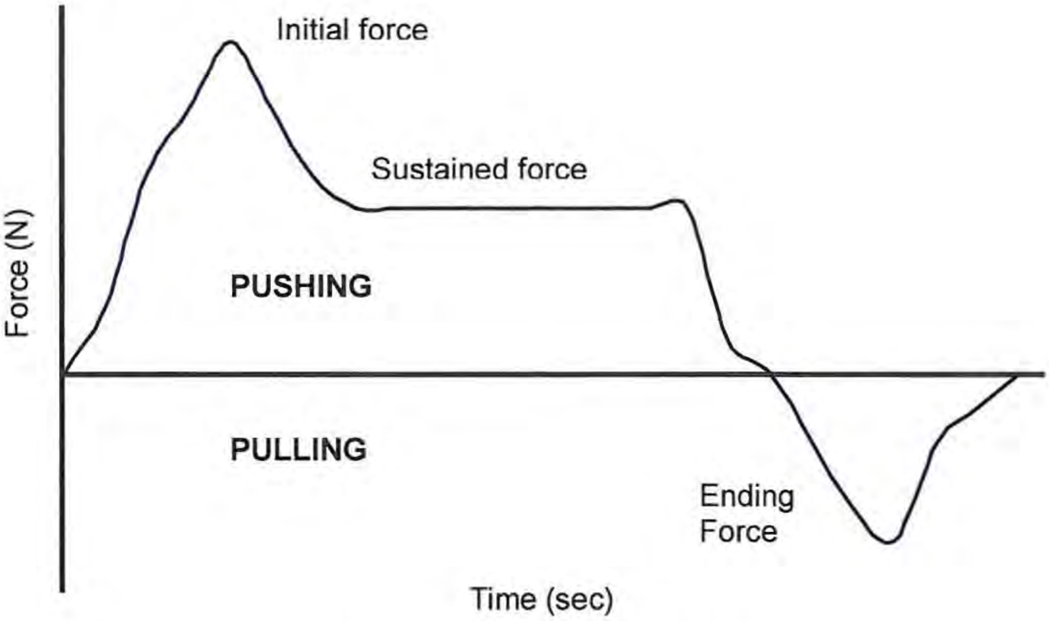

Figure 1: Typical curve of the total exerted force in a pushing task. (Adapted from Jansen et al., 2002)

Laursen and Schibye (2002) argue that the type of floor surface significantly affects the magnitude of push and pull forces, in both the initial and sustained phases of the task. Regardless of the direction of motion, the initial starting phases of a push/pull task will require the greatest use of force (Jung **et al.**, 2005) due to the object's static inertia. Winkel (1983) measured the maximum starting force acceptable to air stewards pushing catering trolleys and found 68N to be the upper limit for repetitive exertions, and a once off limit of 270N. Van der Beek **et al.** (2000) reported initial forces of 278N during initiation of movement of a postal cart weighing in excess of

250kg. Drury **et al.** (1975) and Schibye **et al.** (1997) reported that pushing forces in the initial stage were twice those observed in the sustained phase. The coefficient of friction present for any task will directly influence both the initial and sustained forces required. For instance, Laursen and Schibye (2002) found pushing and pulling forces to be 10-30% greater in the initial stages and 50-100% greater in the sustained phases when pushing or pulling on grass compared to flagstones.

In many work environments, the pushing or pulling tasks will encompass a combination of these force components, depending on the characteristics of the task being performed. Ferreira **et al.** (2004) highlighted that while completing a manual pushing or pulling task, and thus being exposed to the different forces involved, several muscular actions may also be involved. These authors contend that while concentric muscle actions may be the primary mechanism for generating force, isometric force exertions may also be present to stabilise certain body parts, such as the upper extremity, thereby allowing the applied force to be transmitted directly through the object being moved.

Referring to legislation used in the United Kingdom and implemented as a European Directive (90/269/EEC, 1993) regarding manual handling at work (HSE L23, 1998), numerical guidelines for the pushing and pulling of loads are provided based on scientific literature and practical experience (Ferrieria **et al.**, 2004). The guideline refers to the forces applied between knuckle and waist height, and propose reference figures of 25kg (245N) for males and 16kg (157N) for females starting or stopping a load, which decreases to 10kg (98N) for males and 7kg (68N) for females when sustaining the effort. This guideline is aimed at providing a reasonable level of protection for 95% of working males and females. Recommended limits of 225N for initial forces and 112N for sustained forces, and 350N for emergency stops were reported by Jung **et al.** (2005). This current research was interested in isolating the initial, sustained and ending forces of a manual pushing task from a biomechanical perspective, in order to understand these demands within the context of a developing country such as South Africa. Furthermore, due to the lack of published research into the physical impact of initial, sustained and ending forces in pushing activities, and the resulting demands placed on the physiological systems of the body, this project aims to gain a clearer understanding of this relationship.

Impact of Design-Related Factors on Task Demands

Exposure to pushing and pulling can be characterised in terms of intensity, frequency and duration, and to accurately analyse a particular task, information is required on all three. Hoozemans **et al.** (1998) added that should one of these factors deviate from the optimum value, the risk of musculoskeletal disorders increases. This apparently simple evaluation is complicated by each task being executed in unique contexts, hence requiring individual assessment of each component in isolation and in combination. In many cases, particularly in poorer countries, individuals are suffering injuries not as a result of personal inadequacies, but rather due to the misuse of manual assist devices such as trolleys or carts, or alternatively using poorly designed vehicles (Jung **et al.**, 2005). Characteristics of the object being moved can have a significant bearing on the ease of the handling operation: consideration must be given to the design aspects of the object as a means of risk reduction. An assist device that is well designed and maintained will contribute substantially towards efficiency, manoeuvrability and safety, while reducing the physical and perceptual stresses associated with the task (Mack **et al.**, 1995). Among the factors which directly influence the individual's ability to effectively perform a dynamic pushing task, the object load being moved, the frequency at which the task is to be performed and the distance to be covered, along with frictional constraints are the most important. In addition, the design factors that can contribute to ease of use of a manual vehicle, such as handles, brakes and wheels, are commonly neglected components (Jung **et al.**, 2005).

Load

Load mass is the foremost factor in task factors due to its close connection with force requirement. Al-Eisawi **et al.** (1999) established a strong linear relationship between the minimum cart push/pull forces and cart weight. When designing a MHD for a pushing or pulling task, the ergonomist must determine the maximum weight with which to load the cart so that the forces needed to push and pull the MHD do not exceed safe limits (Al-Eisawi **et al.**, 1999). Resnick and Chaffin (1995) found that a cart loaded with a load of 450kg required a force of 243N in order to effectively push it. This finding led Resnick and Chaffin to recommend a load weight limit of 225kg due to biomechanical criteria. Previous research has advocated that regardless of the type of cart in use, load weight should be as low as possible to decrease physical stress (Lawson **et al.**, 1993; Resnick and Chaffin, 1995; van der Beek **et al.**, 2000). Load weights as high as 1500kg have been reported in the literature (Mack **et al.**, 1995), with this author observing many loads well in excess of 500kg in local industry.

Manipulating heavy loads via the use of correct MHDs can be made safer by using appropriate load securing devices, which prevent the loads from falling off, or needing to be held by the operator with one hand. An unbalanced load creates stability problems and requires extra work and handling force (Mack **et al.**, 1995).

Figure 2: Fully loaded industrial pallet jack commonly used in IDCs.

Frequency

As repetition increases, the force a person can exert decreases, particularly as the duration of the task also increases. High repetition increases metabolic demand and reduces the amount of time body tissues have to recover between loadings. The frequency of use of manual handling devices will depend on the industry, and distance over which the task is to be completed. Research to date which report controlling the frequency of push have utilised frequencies as high as one push every 10 seconds (Straker **et al.**, 1997; Shoaf **et al.**, 1997) right down to one push every eight hours (Snook and Ciriello, 1991; Shoaf **et al.**, 1997). Eastman Kodak (1986) suggested that manual vehicles should not be used more than 200 times per day or 25 times per hour. It is important that frequency should not be investigated in isolation to other task factors, as the interaction between frequency, load and distance play a crucial role in determining the total impact of the task on the human operator. As the load and/or distance increase, so the possibility of performing a task at high frequencies diminishes, and vice versa.

Distance

The amount of force a person should apply is directly influenced by how far the equipment must be pushed. The amount of force an individual can sustain decreases as the distance travelled increases. Bearing this in mind, many MHDs in many industries are moved up to 500 metres (Mack **et al.**, 1995), which is well beyond the proposed acceptable limit of 33 metres. Shoaf **et al.** (1997) developed equations to relate factors that will influence an individual's pushing capacity, and the distance multiplier of this equation considered distances between 20 and 65 metres. When creating the L23 Guidelines (HSE, 1998) for acceptable maximum forces in initial, stopping and sustained phases of pushing and pulling, it is important to note that the figures provided are done so with no limit for the distance over which the load should be pushed or pulled, but mention is made that adequate opportunities should be provided in order to rest and recover (Ferreira **et al.**, 2004).

During any pushing performance, the initial and ending forces required within the task are greater than the sustained forces. Due to the high forces experienced during the initial and ending phases, these forces pose the greater concern, and in fact relate to load more than they do to distance. The sustained forces, exerted over any distance are not likely to induce overexertion injuries, fatigue or result in immediate difficulty for the operator.

A function of frequency and distance is the speed at which the task is to be performed. The greater the speed of handling, the greater the stress on the operators involved (Jung **et al.**, 2005). Alternatively, the lower the speed, the greater the impact of load, and the more force that is required in order to maintain momentum.

Coefficient of Friction

The coefficient of friction (also known as the frictional coefficient or the friction coefficient) is a dimensionless scalar value which describes the ratio of the force of friction between two bodies and the force pressing them together. The coefficient of friction (COF) depends on the materials used - for example, ice on metal has a low coefficient of friction (they slide past each other easily), while rubber on pavement has a high coefficient of friction (they do not slide past each other easily). The coefficient of friction is an empirical measurement - it has to be measured experimentally, and cannot be determined by calculations. Rougher surfaces tend to have higher values, while most dry materials in combination give friction coefficient values from 0.3 to 0.6, thus providing optimum friction. It is difficult to maintain values outside this range as movement is restricted by the surface friction being too high or too low.

Two types of friction exist which will affect the use of MHDs: the friction between footwear and the floor, and the friction between wheels and the floor. Ciriello **et al.** (2001) determined the maximum acceptable horizontal force and load weights on floors having different COF. As the COF decreased, so too did the possible initial and sustained forces, along with the maximum acceptable load weight. Frictional forces present between the foot and the flooring are one of the most important factors in pushing and pulling tasks. If the foot slips easily, indicating a low COF between the floor and the shoes worn, or alternatively remains steady and stable (indicating a high COF) the amount of force a person can apply to the equipment will be limited to the amount of traction available. A hard dry floor decreases the operator's physical stress by reducing friction (Laursen and Schibye, 2002), but the recommended COF between shoes and floor is 1.0. This has a trade-off with the rolling friction of the MHD, however, which requires the least amount of friction possible.

Thus it is concluded that shoe-floor friction should be sufficiently large so that operators can use their full physical capabilities in handling the devices (Ciriello **et al.**, 2001). Furthermore, with limited traction, individuals will be unable to optimise their posture and utilise body weight to assist when pushing an object, as the feet will begin to slip, resulting in potential loss of balance and a fall. In any workplace, the COF between the working area floor and the operators' shoes may be low, for any number of reasons. In this situation, the large horizontal forces used to push heavy loads can create a slip hazard (Resnick and Chaffin, 1995). Research has shown that pushing with a high COF (0.6 or higher) can generate as much as 50% more force than pushing with a low COF (0.3 or less). This enhances the friction between the two contacting surfaces significantly, and increases the individual's stability during task performance (Floyd and Thompson, 1998).

Foot to floor traction is an important determinant of push-pull capabilities. Chaffin **et al.** (1999) research shows that healthy males have a push-pull static strength capability of approximately 200N if the COF is 0.3. When the coefficient of friction is greater than 0.6, the mean strength capability increases to 300N. When pushing or pulling heavy trolleys or carts, the required COF between shoe soles and the floor may be greater than 0.8, and muscle strength may not be the limiting factor governing hand forces, but rather the high traction requirements.

The size and composition of the wheels in use affects COF. Hard wheels with high pressures and bearings in good working order reduce rolling friction. In addition, the larger the wheel diameter, the lower the physical stress imposed on the operator (Eastman Kodak, 1986; Al-Eisawi **et al.**, 1999).

Handle Height

Initial research into handle height began as an attempt to determine friction levels required between the floor and the worker to reduce slips, trips and falls during pushing and pulling (Lee, 1982; Chaffin **et al.**, 1983). Lee **et al.** (1991) contended that handle location should not be determined solely by the required friction level, and argued that the potential effect of posture and lower back loading should also be taken into account to reduce lower back injuries associated with pushing and pulling.

Research into the "optimum handle height" for pushing is contradictory. Generally handle height showed an optimum in relation to maximum pushing force at higher handle heights, with many studies suggesting that maximal push force exertion was achieved at handle heights between one metre and shoulder height (Ciriello and Snook, 1983; Kumar, 1995; Kumar **et al.**, 1995). It is evident that handle height affects posture, thus determining force exertion. Chaffin **et al.** (1983) showed a relationship between position of the feet and the maximum pushing force. As the feet are placed further away from the point of application, or if feet are positioned asymmetrically, force increases. Gagnon **et al.** (1992) examined pushing loads onto shelves at different heights. Through repeated measures it was concluded that working height is a critical factor. The upper extremity is predominantly involved in pushing at all heights, but considerably more so at higher levels. Lower positions place higher demands on the lower back, and also require larger amounts of energy. This emphasises the importance of monitoring the physiological cost of a task.

De Looze **et al.** (2000) proposed that factors other than absolute magnitude of exerted forces may be responsible for mechanical loading during pushing and pulling. Direction of the exerted forces in relation to the joints also determines the mechanical load, and should form part of any workplace assessment. Pushing tends to be directed between downward and horizontal for maximum exertion. It was found that the direction of force exertion during pushing became more horizontal as handle height increased. De Looze **et al.** (2000) concluded that force direction and handle height clearly affected the load experienced at the lower back and shoulder.

Skeletal Joint Loading

Back strain is exacerbated by pushing from a low position (Lee, 1982; Chaffin **et al.**, 1983; Gagnon **et al.**, 1992). Gagnon **et al.** (1992) examined shear forces in the lower back during pushing at different handle heights, and found that shear forces increased as handle height increased. This study was later contradicted by de Looze **et al.** (1995), who found lower shear forces for higher handle heights. Lee (1982) and Lee **et al.** (1991) concluded in both studies that an increase in pushing or pulling force was accompanied by an increase in the spinal compressive forces, although greater during pulling.

Workers who frequently pushed and/or pulled reported low-back pain more often than those who did not (Hoozemans **et al.**, 1998). The relationship between occupational pushing and pulling, and general musculoskeletal disorders, rather than lower back pain, has not been extensively studied. It is evident that the shoulders are associated with working above acromion height, twisted postures and isometric loading of the shoulder muscles, all common features of pushing and pulling tasks (Bjelle **et al.**, 1981). However, the extent of the upper and lower extremity involvement is unknown, and investigations must consider this musculature when assessing the impact of any pushing task.

Hoozemans **et al.** (2004) studied the mechanical loading effect of pushing and pulling on the lower back and shoulders. Using theoretical models for the low-back and shoulder, and making adjustments according to the anthropometry of each subject, the authors established that differences between maximum exerted forces for pushing and pulling were dependent on handle height. Initial exerted forces were the highest forces exerted during both pushing and pulling. Handle height also dictates further differences between pushing and pulling in initial shear forces on the low-back, while all factors within the study significantly affected the lumbar spine compressive force. Hoozemans **et al.** (2004) concluded that exerted, compressive and shear forces were differently affected by pushing, pulling and handle height. The results of shoulder joint loading during pushing and pulling indicate that handle height and magnitude of exerted force were significantly related to the mechanical load of the shoulder. This confirmed the findings of Hoozemans **et al.** (1998), who found that mechanical load about the shoulder is kept low by maintaining the wrist, elbow and shoulder close to the line of action of the exerted force.

Musculoskeletal Injuries related to Pushing and Pulling

Work-related injuries are of major concern to industries and academic researchers alike as they strive to reduce workers compensation costs, medical payments and lost work-time costs. Maintaining a good public image is a secondary benefit to reducing work-related accidents and injuries (Mital and Pennathur, 1999). Unfortunately, technology is not always the answer to the problems that arise. In fact, Mital and Pennathur (1999) argue that technology is not only causing new health and safety problems to manage, but has also been ineffective and counterproductive in solving existing problems. A common example is automation, which designers have only been able to apply to simple tasks, thereby leaving the difficult ones for humans to perform.

Research into overexertion injuries related to pushing and pulling activities is limited in comparison to the literature available for lifting. The exertion of force has been associated with musculoskeletal injuries and disorders in lifting research (Mital and Pennathar, 1999); however, in push/pull research, very few studies have provided a specific physical value favouring a qualitative assessment of force.

Chaffin (1987) explained that the risk of health complaints caused by pushing and pulling are associated with two types of hazards. Firstly, the musculoskeletal system can be physically overexerted. Van der Beek **et al.** (1993) established an increased risk of upper body pain, particularly shoulder pain, when investigating occupations which required regular pushing and pulling activity. Secondly, there is an increased risk of slip, trip and fall accidents. Eastman Kodak (1986) reviewed accidents related to manual truck and trolley handling. The researchers concluded that arm, shoulder and back strains associated with slips, trips and falls, and pushing and pulling of trucks should be treated as a major industrial concern. In order to prevent this, jobs need to be designed to enable the worker to carry the tasks out with minimal health risk, in both the short term and the long term (Jansen **et al.**, 2002). Pushing and pulling in the workplace have inherent risk factors, such as direction of exerted force, posture, load and handle height (Hoozemans **et al.,** 1998). In the case of lumbar spine and scapula-clavicle risk, these factors are most critical.

Hoozemans **et al.** (2002) identified a lack of research into the relationship between pushing and pulling tasks in industry, and also of musculoskeletal disorders of the upper extremity. These authors contend that shoulder and other upper extremity complaints have been associated with work executed above acromion height; a recurrent event witnessed in pushing and pulling activities. For these reasons, pushing and pulling efforts could induce serious shoulder complaints, particularly if performed for prolonged periods. A risk factor usually precedes an injury or disorder via accumulation of exposure to risk factors. Pushing or pulling a MHD may stress the soft tissues in the arms, shoulders, back and legs, but the force exposure may be too low for traumatic injury, and given time, the tissues recover. However, repeated exposure to this stress may interfere with the normal recovery process and produce disproportionate responses and eventually an MSD-type injury.

Eastman Kodak (1986) suggested that it is important to identify the weakest muscle groups used in the task when using strength measures to assess the potential for overexertion during handling tasks. These tend to fatigue quicker and are stressed to a higher percentage of the maximum capability. Konz (1998) considered arm and shoulder capability to be the limiting factor for pushing or pulling exertions. This is particularly the case when the activity is repetitive, posture is poor and handle height is not within the zone of strength.

Working Posture

Resnick and Chaffin (1995) asserted that in order to predict the forces and biomechanical stress that operators will be exposed to when using push/pull carts and manual handling devices, knowledge of the postures resulting in maximum force is crucial. Maximum performance and minimal stress facilitates designing jobs and work areas that allow workers to use these postures. MacKinnon (1998) stated that the stability of an operator within a workstation impacts significantly on the magnitude of the horizontal force production. Unless a body is stable when it produces force, much of the effort will be wasted. When attempting to exert large or maximal forces, the operator should opt for a posture which creates a large base of support. Maximum stability is achieved when the line of gravity intersects the base of support at a point which allows a large range of motion within the base area, in the direction of forces causing movement (Luttgens and Hamilton, 1997).

A vital consideration in any risk evaluation is the working posture adopted. Tasks which require an awkward posture, particularly at the extremes of range of motion, can lead to imbalances within the system, which may result in joint function degradation (Bridger, 2003). The musculoskeletal injuries incurred as a result of MMH have stimulated extensive research into the capacities and limitations of the human operator. With specific reference to pushing and pulling, Fothergill and associates (1991) reported that previous studies carried out have focused on two-handed pushing and pulling strength; furthermore the studies have been limited to defined, rigid postures. Therefore

> "*whole-body strength data has been more representative of the conditions imposed by experimental constraints rather than of real strength capabilities of human beings in the freely chosen postures that they would normally use in real-world working tasks*" (Fothergill **et al.**, 1991, p 563).

The aim of this study is therefore to allow the replication of postures that are freely chosen by workers within industry with the purpose of performing the task to the best of their abilities. The posture assumed during pushing activities has been shown to have different effects on maximal strength exertions. Nadeau and Gagnon (1996) proposed that workers tend to exert the maximal push force when using the whole body, yet when allowed to choose a preferred (free) method, chose not to incorporate the lower limbs, and ultimately produced lower forces. Results from this study indicate that in order to push loads more easily, one must combine the motions of the lower limbs, trunk and upper limbs, yet this does not happen freely.

Maintaining a Good Working Posture

Balance is defined by Luttgens and Hamilton (1997) as the ability to control the equilibrium of a body, under both static and dynamic conditions. In order to achieve this control, the individual is required to manipulate the equilibrium of the body through movement (Floyd and Thompson, 1998). It is possible to manipulate this equilibrium through a conscious increase in the base of support. Broadening the stance taken or lowering of the centre of mass of the body, by assuming a lowered body position maximises stability. Stability of operators, particularly in MMH tasks, is critically important in the prevention of falls (Holbein and Redfern, 1997).

The human body is a mechanical system which obeys physical laws. Most human postural and balance control mechanisms are taken for granted, as they operate outside the level of conscious awareness. When these mechanisms fail, as in slipping or losing balance, Bridger (2003) contends that this is a reminder of human's physical limitations. The body is capable of withstanding a limited range of physical stresses, imposed both externally and internally. In order for the body to be stable, the combined centre of gravity (COG) of the various body parts must fall within the base of support. The base of support is essentially the full area of stability, which is defined as the perimeter of the foot contact area (Bridger, 2003), although the area of functional stability is likely to be considerably smaller. During pushing and pulling tasks in industry, workers often assume postures which may exacerbate the potential to slip, trip or fall (Holbein and Redfern, 1997; Bentley and Haslam, 2001; Bridger, 2003). This is done to facilitate the overcoming of the inertia of the object to be moved, as well as maintaining the momentum.

Figure 3: Posture assumed during a pushing task at a local automotive industry.

Bridger (2003) explained that the size of the base of support is fundamental to the stability of any individual, as it influences the adopted posture during the execution of any activity. When an individual, whose mass is supported entirely by the feet, increases the distance between the feet, the base is widened which in turn greatly improves equilibrium (Adrian and Cooper, 1996). When upright, the centre of mass falls directly through the feet, which are acting as the base of support, ensuring that stability is maintained.

As a guideline, the centre of mass tends to be located at between 55 and 59% of an individual's stature, dependent on the sex. Raising the centre of mass beyond this increases the possibility of an individual 'toppling', through loss of stability both vertically and horizontally. Increasing the distance between the centre of mass and the base of support, increases the moment of toppling, resulting in reduced stability; alternatively, lowering the centre of mass improves an individual's balance and increases stability (Hay and Reid, 1988).

Maintaining the centre of mass within the base of support, in order to preserve stability and balance is problematic when performing tasks at the limit of human posture capability (Luttgens and Hamilton, 1997). During labour-intensive work, it is unlikely that at all stages of the task, the centre of mass will be located within the base of support, due to the dynamic nature of tasks. The nearer the centre of mass comes to moving beyond the base of support, the more unstable the equilibrium becomes. Once outside the base of support, stability is lost, thereby significantly increasing the risk of slip, trip and fall (Adrian and Cooper, 1996). This potential risk is dramatically increased when pushing and pulling, as the postures adopted vary, frequently resulting in the centre of mass falling outside the base of support (Todd and James, 2004). Resnick and Chaffin (1995) argued that dynamic push/pull movements further increase risk. Postures and forces continuously change during an exertion, and it is unlikely that subjects would be able to assume an optimal posture for the full duration of the task.

Slip, Trip and Fall Accidents

Slip, trip and fall (STF) accidents are not a new occupational concern. In fact since 1985 scientists and workplace managers began to recognise the problem of STF accidents within the workplace (e.g. Buck and Coleman, 1985). Unfortunately though, until recently, the technology required to accurately assess and evaluate potential causes and underlying reasons for more complex STF accidents has not been available. Leamon and Murphy (1995) explained that despite the recognition of slips and falls as a serious problem by researchers, industry and the public have been lacking the initiative to reduce these incidents. Nevertheless, STFs continue to be a serious and costly problem for society, particularly in terms of individual suffering and social costs of medical care, and any cost that can be avoided through appropriate intervention should constitute an imperative for action.

It has been reported by Courtney and Webster (1999) that within the workplace, slips and falls are responsible for many of the most severely disabling occupational injuries. The annual direct cost of occupational injuries in the USA due to STFs has been estimated to be in excess of US $6 billion (Courtney **et al.**, 2001). Bentley and Haslam (2001) confirmed the rising prevalence of STF accidents, reporting that these accidents are also the leading cause of occupational injury in the UK, accounting for 20% of all accidents at work. However, recent figures from the Health and Safety Executive (2005) reveal that this statistic has risen to 33% of all reported major injuries and the costs incurred by employers and the health service are estimated at £645 million. Leamon and Murphy (1995) offered a possible explanation for the disparity in public perception and this occupational concern, and that is that people's everyday experience of minor slips and falls infers a consequential ideology that serious slipping and falling have a comparable and unavoidable cause.

Awkward pulling or pushing postures can increase the likelihood of musculoskeletal injury, and the threat of STF accidents. This risk is further magnified when individuals are required to push or pull an object from a stationary position, as it then becomes necessary to overcome the object's inertia, and any frictional resistance, by applying additional force, before setting it in motion (Hoozemans **et al.**, 1998).

Other risk factors for STFs are related to uneven surfaces, poor housekeeping, inadequate control of posture and poorly designed flooring, which can have interrelated risk factors and which could have cumulative effects. As Chang (2002) points out, there is no single cause of all STF accidents, hence there is no single solution. In fact, the complexity of STF accidents reveal how much researchers in ergonomics, biomechanics and occupational health still have to learn about the causes of these accidents.

Gait Pattern Responses during Dynamic Pushing

Humans rely on numerous sensomotoric systems to maintain upright static posture and dynamic balance during locomotion. The sensory input from vestibular organs, vision and proprioceptive receptors are rapidly and accurately processed by the central nervous system. When this balance and posture is challenged, a co-ordinated neuromuscular response is needed to re-establish the balance and avoid a fall and subsequent injury (Kumar, 2001). Protective gait adaptations are aimed at regulating gait in hazardous conditions. Gait patterns are freely chosen by individuals and operators depending upon the conditions under which they are required to perform. Zatsiorsky **et al.** (1994) contended that individuals chose their gait patterns freely, and that responses were not mechanically pre-determined, regardless of whether walking speed is self-selected or imposed. Individuals choose the gait pattern which optimises body stability, strength exertion and minimisation of energy expenditure. Winter (1991) mentions five major motor functions during the gait cycle in order to achieve safe and efficient propulsion of the body. These functions are: maintenance of support of the upper body; maintenance of upright posture and balance of whole body; safe ground clearance and gentle landing; generation of mechanical energy to maintain forward velocity; and absorption of mechanical energy for stability. Whilst pushing or pulling, particularly heavy loads, a number of these functions are compromised by the necessity for an individual to shift the centre of balance to set the MHD in motion or maintain that motion, or alternatively to maintain adequate control and handling of the MHD.

Researchers have frequently commented on the ability of the human body to conserve or optimise its energy consumption (Inman, 1966; Pierrynowski **et al.**, 1981). Holt **et al.** 1991 and Bunc and Dlouhá (1997) made mention that in addition to these gait factors, the stride frequency and stride length have a consequential effect on metabolic cost. In general, people tend to take longer strides and walk at higher velocities with greater cadences under natural conditions (Sun **et al.**, 1996). Of the gait characteristics commonly assessed, walking speed, cadence and stride length, all of which are useful parameters for describing human walking, only two of them are independent.

Stride Length

The stride length of an individual is determined by measuring the distance from heel strike on the right foot, to heel strike on the right foot again. Whittle (1993) stated that the approximate range (95% limits) for free-speed walking by normal male subjects between the ages of 18 and 49 was a stride length of between 1.25 and 1.82m.

Cadence

The gait cadence is the number of steps taken in a given time, usually steps per minute. The approximate cadence range (95% limits) for free-speed walking by normal male subjects between the ages of 18 and 49 was 91-135 steps per minute (Whittle, 1993). To the best of the author's knowledge, no research has been published which has specifically focused on the role of gait, and the role of these two factors in pushing and pulling of manual handling devices. A void in the literature is thus created, which needs to be filled through extensive research and publication. It is anticipated that an individual will adapt their stride length according to the load and frequency, or the load/frequency combination. This adaptation will still aim to optimise energy expenditure, but may change the biomechanical demands of the lower extremity joints, thereby increasing the risk of injury. Alternatively, any changes in gait patterns are likely to increase the chances of individuals experiencing STF accidents due to the "unnatural" patterns adopted.

PHYSIOLOGY OF PUSHING AND PULLING

Introduction

The studies into pushing and pulling have primarily focused on the problems associated with pushing and pulling from a biomechanical (Laursen and Schibye, 2002; Hoozemans **et al.**, 2002; Jansen **et al.**, 2002; Kingma **et al.**, 2003; Hoozemans **et al.**, 2004) or psychophysical perspective (Ciriello **et al.**, 2001; Haslam **et al.**, 2002;

Kingma **et al.**, 2003; Ciriello, 2004 and 2005). Very little research has investigated the energy cost of pushing and pulling tasks or the physiological responses to pushing and pulling tasks in terms of the impact of frequency and load on physiological cost. However, changes in working frequency and load during pushing tasks will influence cardiovascular responses, which provide a direct indication of changes in the body's physiological functioning. Mital **et al.** (1989) described the physiological response to lifting tasks as being limited by the individuals' capacity to transport oxygen, with heart rate being a common indicator of physiological stress. As was determined in lifting tasks, there are also physiological limits that should not be exceeded for pushing tasks. Frequency and load are two key task factors that are commonly altered in order to maintain a desirable working heart rate. Through the manipulation of load and frequency, intensity can be maintained within acceptable limits. As yet, limited pushing and pulling studies have focused on the interaction of these two task-related variables.

By assessing the impact of frequency and load on physiological responses, optimal load-frequency combinations can be established. Authors (Mital **et al.** 1997; MacKinnon, 1999) have shown that in lifting activities, a rise in lifting frequency increases the physiological strain on the body, evidenced through increases in heart rate, energy expenditure and perceived exertion. Loads pushed and pulled in industry vary substantially, with loads of up to 1500kg witnessed within local manufacturing industries. In lifting research, high frequency, low load tasks have often elicited similar responses to low frequency, high load tasks (Samanta and Chatterjee, 1981; Khalaft **et al.**, 1999). Heavier loads tend to impact more on the biomechanical aspect of the worker, increasing fatigue and muscular pain, nonetheless, the interaction of these two variables is important when evaluating physiological strain in working situations.

Physiological Approach

Applying ergonomic principles is vital in any working environment, as it integrates knowledge of the human operator, the activity and the specific environment in which the operator is completing the activity (Ayoub, 1992), and attempts to match the worker's physical, physiological and mental capabilities to the task demands (Garg **et al.**, 1978). Dempsey (1998) stated that the primary goal of the physiological approach is to design tasks which are within certain physiologically acceptable limits. This is to prevent the high physiological costs associated with elevated levels of fatigue. The development and introduction of automation and modern technology has contributed to a decrease in heavy physical work; nevertheless some physical work is still required in many occupations. This is particularly the case in developing countries where a large percentage of the population are involved in physically demanding work (O'Neill, 2005).

Scott and Christie (2004) argued that it is necessary to establish basic, yet reliable measures of a worker's physiological response to manual tasks. Determining the energy cost of any given task performed in industry is difficult, due to the impact of the environment on testing procedures as well as the possible hindrance technology would impose on the working process. However, knowledge of energy cost while performing the task is critical, as when energy expenditure is excessive it is detrimental to the individual worker and ultimately impacts negatively on productivity.

A limitation to the use of physiological criteria is the lack of demonstrated relationships between physiological load and injury rates (Dempsey, 1998). Sanders and McCormick (1992) stated that the metabolic processes being carried out within the muscle must be supported by the cardiovascular system of the body. Knowledge of these physiological responses will aid the understanding of how physical work manifests as physical strain. Needless to say, the physiological criterion proposed by Dempsey (1998) is therefore important in preventing fatigue and discomfort, of which the cumulative effects are likely to contribute towards compensable injuries.

Studies of physiological demands

Early studies investigating the physiological response to pushing and pulling (Williams **et al.**, 1966; Wyndham and Heyns, 1967; Haisman **et al.**, 1972; Haisman and Goldman, 1974; Datta **et al.**, 1983) revealed that when pushing or pulling handcarts, as loads were increased, the demand placed on the cardiovascular system increased. Williams **et al.** (1966) found that when pushing well lubricated mine carts loaded with 2000lbs, experienced mine workers reached oxygen consumption values of 1.40L.min^{-1}, a value which would classify the task as 'heavy' according to current guidelines. In possibly the most comprehensive study of energy expenditure in pushing, Wyndam and Heyns (1967) investigated mechanical efficiency and energy expenditure during the pushing of mine cars at different speeds and loads. An understanding of the optimum human mechanical efficiency would go a long way to ensuring that the physical capacities of workers were not exceeded. By investigating 25 load/speed combinations, Wyndham and Heyns (1967) found increases in speed and or increases in load brought about an increase in oxygen consumption. In addition, at higher speeds with greater loads, the oxygen consumptions exceeded 2.0Lmin^{-1}, which was more than 60% of the subjects mean maximum oxygen uptake.

Haisman **et al.** (1972) investigated the energy expenditure of pushing 50kg in 2- and 4-wheeled handcarts on a treadmill, and found mean energy expenditure for all carts of 511W, or 7.50kcal.min^{-1}. The applicability of such findings must be considered, however, as the treadmill protocol may have been unnatural for many of the subjects, resulting in elevated physiological responses. Ciriello and Snook (1983) investigated the impact of frequency on oxygen consumption and heart rate responses, using psychophysically determined maximum acceptable loads, and noted that both HR responses and energy expenditure decrease as the pushing frequency decreased. At a frequency of four pushes over 7.6m.min^{-1}, the male subjects recorded an average oxygen consumption of 1574mL.min^{-1} and a heart rate of 127bt.min^{-1}. The female subjects achieved far lower oxygen consumption values (1181mL.min^{-1}), but higher heart rate values (137bt.min^{-1}) for the same frequency and distance. A decrease in frequency to one push every 22 seconds resulted in a drop in average heart rate and oxygen consumption for both males and females. In the 1990s, when the problems associated with pushing and pulling attracted much attention in the literature, only two studies to the author's knowledge looked specifically at the physiological cost of pushing.

Smolander **et al.** (1995) examined the physiological cost of snow pushing and found the task to be taxing to the physiological systems of the body, requiring oxygen consumption values of $2.6L.min^{-1}$, or 75% of maximum. Frings-Dresen **et al.** (1995a) examined the energy expenditure of refuse collecting, and the push/pull tasks were found to induce substantially lower heart rate and oxygen consumption values ($1.18L.min^{-1}$). Garcin **et al.** (1996) aimed to assess the physiological strains experienced while pushing and hauling. The experiment design meant that subjects were only ever experiencing the effort required for the sustained phase of any pushing task, and not the full complexity of the initial, sustained and ending phases. Fundamental characteristics of a pushing task, such as inertia and rolling friction were notably absent in this project design. In addition, this experimental design meant that it was more the effect of the speed that influenced the physiological responses, than the impact of the load or the task, since the design represented more of a hold/ carrying task than a pushing task. Nonetheless, interesting results were achieved, with the experienced subjects demonstrating heart rate and $\dot{V}O_2$ values well in excess of the untrained subjects, despite minimal differences in the speed/load combinations. The highest mean heart rates ($139bt.min^{-1}$) were achieved by the endurance trained subjects while walking at $4.7kmh^{-1}$ while pushing (holding) a load of 10kg. This corresponded with a mean $\dot{V}O_2$ value of $32.10ml.kg^{-1}.min^{-1}$. The sedentary subjects recorded the highest mean HR of $111bt.min^{-1}$ while pushing 7kg sustained force at $4km.h^{-1}$, corresponding with a $\dot{V}O_2$ value of $15.68ml.kg^{-1}.min^{-1}$.

Energy expenditure is individual and task specific, and at the same energy expenditure levels individuals are strained differently, and therefore energy expenditure needs to be expressed as a percentage of an individual's maximum oxygen uptake ($\dot{V}O_2$). The risk of musculoskeletal disorders increases when regular signs of fatigue are ignored and the workload is not adjusted accordingly (Hoozemans **et al.**, 1998). Despite the efforts of the authors above to get a comprehensive understanding of the energy costs associated with pushing or pulling tasks, or establish effective guidelines which could be applied across industry, Hoozemans **et**

al. (1998) argued that "studies that have investigated the physiological effect of different pushing and pulling tasks are scarce and that only a few risk factors can be identified". This statement is even more alarming considering that Wyndham and Heyns (1967) stated that "it is surprising to find so few references in the literature about energy expenditure in the task of pushing".

Models for understanding physiological demands (HR,EE,$\dot{V}O_2$,V_E)

Kilbom (1995) described how, when performing physical work, the human body is not only required to move itself in a controlled sustainable posture, but often also to move other objects. Burdorf **et al.** (1993) stated that body posture can alter the force requirements of a manual task; in many cases, this can create a posture which places additional strain onto the structure and musculature of the body. In dynamic tasks such as pushing, which also comprise static components, the body is capable of assuming any number of postures, some changing during the task, while others remain fixed. Van der Beek **et al.** (2000) stated that isometric muscle activity in the trunk and upper extremities accompanying pushing might influence the subject's cardiovascular system. Ayoub and Mital (1989) showed that the physiological costs of a task are higher in non-erect postures than in an upright standing posture. These authors therefore suggest that pushing tasks should be exerted as near to an erect position as possible, with pulling tasks avoided entirely. However, this finding may not be the case when a task is evaluated from a biomechanical perspective, since force production will be lower in an upright posture, than a posture which allows full utilisation of body mass. The physiological effects of static work are well known and include, amongst others, the lack of oxygen supply to the muscles which accelerates the loss of strength, ultimately leading to pain (Ayoub and Mital, 1989). Further, it has been found that dynamic work induces proportional increases in energy expenditure and heart rate, whereas static work induces a heart rate increase greater than the oxygen uptake increase (Monod and Pottier, 1981). The human body reacts to this demand with complex cardiovascular, respiratory and metabolic responses. The interaction between these variables and the individual's working capacity will ultimately determine the efficiency of the response, and either allow the body to cope, or experience strain.

Heart Rate

The most commonly assessed physiological variable to evaluate task demands is heart rate, as it has been shown to give an accurate indication of physical strain (Garg **et al.**, 1978; Sanders and McCormick, 1992; McArdle **et al.**, 2001). Heart rate monitors are a popular and common tool utilised to determine the degree of physical exertion. They are non-invasive and can collect data continuously over extended periods of time, and have shown reproducible results (Vuori, 1998). When work demands result in individuals with excessively high 'working' heart rates, they run the risk of inadequate contractions of the heart muscle, thereby reducing the oxygen supply to the working muscles (Tortora and Grabowski, 2000), leading to fatigue and muscle weakness, both of which are detrimental to physical performance.

Heart rate recordings are a valuable measure in ergonomic research due to the relationship that exists between heart rate and oxygen consumption. It is acknowledged that heart rate and oxygen consumption ($\dot{V}O_2$) relate linearly throughout a large range of aerobic exercise intensities (Maas **et al.**, 1989; Bot and Hollander, 2000; McArdle **et al.**, 2001). Heart rate is used to estimate the physical strain during work or daily activities (Åstrand and Rodahl, 1986), as it gives researchers the opportunity of an easy, non-invasive and inexpensive determination of energy expenditure which is calculated from $\dot{V}O_2$. Therefore, Capodaglio **et al.** (1997) advocated the use of heart rate (as an indirect measure), and the relationship between heart rate and $\dot{V}O_2$ to effectively predict individuals' working energy expenditure and physiological cost. In this regard, physiological guidelines based on heart rate responses and corresponding oxygen uptake have been developed, in order to classify work from 'light tasks' to 'extremely heavy' tasks, an example of which is presented in Table I.

Table I: Heart Rate (HR), Oxygen Consumption ($\dot{V}O_2$) and Energy Expenditure (EE) Guidelines for Prolonged Working Periods

(from Åstrand and Rodahl, 1977 and McArdle **et al.**, 2001)

	Åstrand and Rodahl (1977)		**McArdle et al. (2001)**	
Type of Work	**Heart Rate (HR) bt.min^{-1}**	**$\dot{V}O_2$ (L.min^{-1})**	**$\dot{V}O_2$ (L.min^{-1}) Males**	**EE (kcal.min^{-1})**
'Light'	< 90	< 0.5	0.4 – 0.99	2.0 – 4.9
'Moderate'	90 – 110	0.5 – 1.0	1.0 – 1.49	5.0 – 7.4
'Heavy'	110 – 130	1.0 – 1.5	1.50 – 1.99	7.5 – 9.9
'Very heavy'	130 – 150	1.5 – 2.0	2.00 – 2.49	10.0 – 12.4
'Extremely heavy'	150 – 170	> 2.0	≥ 2.50	≥ 12.5

Åstrand and Rodahl (1986) suggested that working heart rates between 90 and 130bt.min^{-1} should be the upper limit for 'steady-state' work. In contrast Kumar **et al.** (2000) reported an acceptable working heart rate of 104 to 114bt.min^{-1} for palletising tasks. However, physiologists have suggested $\dot{V}O_2$ should be used to determine work intensity. $\dot{V}O_2$ can be represented in either absolute or relative terms (to an individual's body mass), and relative is more frequently reported as it permits researchers the opportunity to compare individuals.

Although the use of heart rate to estimate energy cost appears practical, McArdle **et al.** (2001) caution that it has limited research purpose because it has only been validated for a few general studies. In addition, heart rate is known to be affected by a number of factors including age, sex, level of fatigue, posture, training status, static or dynamic activities, psychological factors such as motivation and the size of the muscles involved in the activity (Maas **et al.**, 1989; Bot and Hollander, 2000; McArdle **et al.**, 2001; Scott and Christie, 2004). Furthermore, to the best of the author's knowledge, no published research exists which validates the use of heart rate as a predictor of oxygen consumption in pushing and pulling studies.

Oxygen Consumption and Energy Expenditure

Industries' productivity can be directly related to the energy cost of performing the necessary tasks. This energy cost is however difficult to assess, yet it is vitally important as when energy expenditure becomes excessive it limits an individual's capacity and increases the frequency and number of accidents and subsequent injuries. Direct assessments of energy expenditure and oxygen consumption provide further and more accurate investigation of tasks' physiological cost. According to Saha **et al.** (1979) an acceptable workload represents the level of physical activity that can be sustained by an individual for eight hours in a physiologically steady state and which would not cause fatigue or discomfort. The acceptable workload is generally expressed in terms of relative load ($\%\dot{V}O_2$ max) or in comparison to pre-determined guidelines, as seen in Table I. Depending on the kind of tasks being performed, different values can be considered as acceptable workload for an 8-hour day. A mean limit of $30\%\dot{V}O_{2max}$ is generally considered to be the energetic load limit for tasks performed over eight hours a day, as Åstrand and Rodahl (1990) stated that with oxygen consumption greater than $50\%\dot{V}O_{2max}$ it is impossible to obtain a steady state for a whole day.

Energy expenditure can, however, be affected by more than just the physical requirement of the task. Although physical exertion has the most profound effect on human energy expenditure, accounting for between 15 and 30% of a person's total daily energy expenditure (McArdle **et al.**, 2001), dietary-induced thermogenesis, climate and pregnancy can all alter the energy output. By converting the oxygen consumption ($\dot{V}O_2$) values attained from direct assessment of the physiological responses, and converting them to kilo-calories, a measure of an individual's energy expenditure during the course of the task is attained.

Frings-Dresen **et al.** (1995b) examined the physiological cost of refuse collecting, which is a task that combines lifting, carrying, pushing and pulling, and found that the majority of workers exceeded the energetic limit of $30\%\dot{V}O_{2max}$ for the task, with $\dot{V}O_2$ values ranging between $0.97L.min^{-1}$ and $1.18L.min^{-1}$. Van der Beek **et al.** (2000)

examined male and female postal workers handling wheeled cages and found the task to be physiologically demanding. Male oxygen consumption values increased from 0.80L.min^{-1} at a load of 130kg to 1.3L.min^{-1} at a load of 550kg, when pushing over a distance of 11 metres at a frequency of two pushes per minute. The authors compared these findings to established guidelines, and found that the push/ pull tasks would only have been acceptable if workers spent less than two hours performing the task, with the remainder of the day spent on less strenuous tasks. In addition, the authors found that as the load increased, so too did the individual's working heart rate, with male subjects reaching 69% of maximum while pushing the heaviest load of 550kg as opposed to 56% when pushing the lightest load of 130kg; the female subjects reached 78% of maximum at the highest load and 61% at the lowest load. Although useful as a means of comparison, it must be recognised that only four male subjects were used in this study, making applicability difficult.

Despite these findings, no research has been able to conclude that pushing (or pulling) is physiologically less taxing than lifting, lowering or carrying. Mital **et al.** (1997) provided some extensive physiological guidelines for lifting, lowering and carrying tasks at high frequencies, which have been summarised in Table II below.

Table II: Guidelines of male Heart Rate (HR) and Oxygen Consumption ($\dot{V}O_2$) values for lifting, carrying and lowering tasks at a frequency of 14/min, for the 90th and 50th population percentiles.

	Lifting		**Lowering**		**Carrying**	
	$90^{th\%ile}$	**$50^{th\%ile}$**	**$90^{th\%ile}$**	**$50^{th\%ile}$**	**$90^{th\%ile}$**	**$50^{th\%ile}$**
HR (bt.min^{-1})	127	153	105	133	111	134
$\dot{V}O_2$ (L.min^{-1})	1.41	2.01	1.11	1.65	0.74	1.29

The values given for the 90th percentile lifting are similar to those that have occurred during high load / low frequency pushing tasks (van der Beek **et al.**, 2000; Frings-Dresen **et al.**, 1995a,b) or alternatively low load / high frequency pushing tasks

(Ciriello and Snook, 1983). Attaining optimum responses through a combination of load and frequency would go a long way to reducing the potential metabolic cost of pushing tasks in industry.

In order to steer away from the biomechanical demands of lifting and carrying tasks, it can be successfully argued that pushing has limited the strain experienced by individuals. However, debate still continues as to whether the forces experienced, particularly in the lower back, fall within acceptable limits. Unfortunately the same cannot be said from a physiological perspective. As yet there is little or no evidence to suggest that either pushing or pulling is physiologically less taxing than the other, or even that pushing and pulling has eliminated the physiological strain experienced during lift and carry tasks. This research aims to shed some light on the physiological impact of pushing dynamically, and thereby reduce the amount of uncertainty or confusion that exists in this common industrial task.

PUSHING VS. PULLING

There is considerable concern for the lack of consensus in the pushing and pulling literature, and Al-Eisawi **et al.** (1999) pointed out that research into pushing and pulling has failed to reach a conclusive finding as to which results in the greatest force production. Under static conditions, some authors have found pulling strength to exceed pushing strength (Kumar, 1995), while others have found no differences (Daams, 1993; James **et al.**, 2005). When assessing pushing and pulling tasks dynamically, there is even greater debate, with some researchers establishing push forces as being greater than pull forces (Snook and Ciriello, 1991), pulling exceeding pushing (Lee **et al.**, 1991) and no difference (Ciriello **et al.**, 1993). The source of such debate and contention seems to arise from differences in methodology. Daams (1993) contended that the methods used to describe research methodologies vary substantially, and in particular, descriptions of the posture utilised. It is therefore critical that research into this field must be focused on creating a clear understanding of the postures and forces involved in both pushing and pulling, before any sound recommendations can be made to industry that may benefit the human operator.

Results from research taking a biomechanical approach have frequently advocated that it is better to push than to pull; yet there is very little evidence to support this from a physiological perspective. In order to better understand the physiological demands of pushing and pulling tasks, it is imperative that the mechanisms of fatigue are understood (Todd, 2005). This understanding coupled with that achieved from a biomechanical perspective must then be applied *in situ*, when designing pushing and pulling tasks.

Taking cognisance of the previous research and recommendations, primarily from a biomechanical perspective, this study aims to isolate pushing tasks and comprehensively assess the biomechanical and physiological responses to the task under varied conditions evident in practical use everyday.

PSYCHOPHYSICAL EVALUATION OF PUSHING AND PULLING

Evaluations of human operators in any working situation need to be holistic in nature. In order to achieve this, it is important to include assessments of how the subject perceives the task they are required to perform (Straker **et al.**, 1997). The actual strain resulting from executing the task may be difficult to measure, but the apparent demands of the task and the person's perceived capacity to deal with the demands can be evaluated through subjective perceptual scales. Sanders and McCormick (1992) emphasised that the psychophysical approach provides the subjects an opportunity to subjectively provide feedback regarding the biomechanical and physiological stresses they experienced while performing the task. Perceptual scales are frequently used to evaluate the well-being of workers during the execution of a task, or at the completion of a task. These insights allow an understanding of the individual's perception of the task at hand (Borg, 1973; Wilson and Corlett, 1995), as it is recognised that the individual's interpretation of signals from the body, as well as the individual's commitment and motivation will determine the quality and standard of performance. A number of perceptual scales have been developed, aimed at measuring perceived strain, exertion or discomfort experienced by the individual while partaking in a specific activity. With psychophysics, aspects of pushing and pulling can be identified which may influence maximum exerted forces. These aspects can be considered as risk factors for MSDs when push/pull tasks are designed, such that the actual forces required to be generated may exceed maximum acceptable forces (Hoozemans **et al.**, 1998).

Pushing and pulling tasks have been studied extensively from a psychophysical design perspective, most notably by Snook, Ciriello, Mital and colleagues. The Liberty Mutual studies, commonly referenced in all manual work literature, have attempted to develop guidelines for the evaluation and design of manual handling tasks that are consistent with worker capabilities and limitations (Snook, 1987). These guidelines have however taken a predominantly psychophysical approach to determining limitations, and, although contributing substantially to the body of knowledge around manual handling, have not suitably addressed the biomechanical and physiological issues of manual handling, and in particular pushing and pulling tasks. Tasks which individuals deem to be psychophysically acceptable could still be of concern due to the biomechanical and physiological demands. Snook (1978) produced a series of tables for horizontal pushing and pulling based on the psychophysical methodology of perceived Maximum Acceptable Forces (MAF). Later on, following additional experimentation, Snook and Ciriello (1991) updated the original findings. The methodology employed in these studies was considered to be the most realistic representation of dynamic *in situ* pushing and pulling tasks. The design limit tables (Snook and Ciriello, 1991) provide MAF of initial push and pull forces for 90% of the American male and female industrial population for a range of frequencies, distances and handle heights. These tables highlighted that as frequency increased, distance increased or handle heights moved above shoulder or below waist height, so the MAF decreased, for both working populations. Mital **et al.** (1997) in their guide to manual materials handling, adjusted the Snook and Ciriello (1991) data in order that the physiological design criteria were not violated. However, the authors did not consider biomechanical design criteria as limiting factors in pushing and pulling tasks.

Rating of Perceived Exertion (RPE)

Borg (1970) developed the Rating of Perceived Exertion (RPE) scale, based on the individuals' perception of the level of exertion required to carry out the required task. The scale was intended as a perceptual measure used to complement the measured physiological factors of the task (Borg, 1978), and to provide further insight into the demands placed on an individual by the particular task. MacKinnon (1999) added that the RPE scale is useful as part of a research set-up, as it is versatile and does not interfere with the task being completed, and can thus be easily used.

The RPE scale is a well accepted accompaniment to physiological research, since it can be utilised as an indicator of physical strain being experienced by the individual. The RPE scale is set up so that the ratings of exertion from 6 to 20 are linearly related to heart rate responses at that level of exertion (Borg, 1982). In order to assist individuals in best approximating the intensity of their effort, verbal explanations are provided to every second number, ranging from 'very, very light' to 'very, very hard'. The relationship between heart rate and RPE has been shown in numerous sporting activities (Martin and Anderson, 2000) at differing intensities (Herman **et al.**, 2003) and at different absolute and relative intensities between genders performing the same task (Robertson **et al.**, 2000). However, very few studies have examined the RPE/HR correlation in manual materials handling. Robertson (1982) showed from a review of numerous studies that correlations of between 0.42 and 0.94 could be achieved between heart rate and RPE in tasks such as lifting and carrying. MacKinnon (1999) reported that a direct prediction of heart rate from RPE ranged from a strong correlation of 0.68 in sweeping tasks to a weaker correlation of 0.11 in load carriage tasks, indicating the role of an individual's perception of a task in formalising a subjective evaluation. Resnick and Chaffin (1995) measured the rate of perceived exertion during pushing and pulling of manual handling devices, and found the arms and legs were the body parts most stressed; however, no heart rates were recorded and so no relationship or correlation could be established. Unfortunately, current literature does not show that a relationship has been established in either pushing or pulling tasks performed *in situ* or in the laboratory. Olivier and Scott (1994), however, caution that despite the correlation between heart rate and RPE, this is not an indication that the variables are related to each other.

Body Discomfort

Due to the nature of MMH activities and the individual responses associated with these tasks, it is likely that during the performance of the task, body discomfort will be experienced. Corlett and Bishop (1976) explained that discomfort is the total of all multiple unpleasant sensations received via the special senses from the different body areas, resulting in a 'gestalt' perception of overall discomfort. Kumar **et al.** (2000) elaborated that perceptions of task demands are subjective, and therefore influenced by more than biomechanical and physiological factors. Discomfort is an important indicator of incompatibility between the worker and the task, thereby possibly predicting musculoskeletal injuries resulting from sub-optimal postures or highly repetitive tasks, indicating the need to adjust the workstation or the job to suit the operator. The Body Discomfort Map is a modified version of the Body Discomfort Scale proposed by Corlett and Bishop (1976), and is utilised extensively in ergonomics investigations in order to allow individuals to identify specific areas of the body where discomfort is experienced, as well as to rate the degree of discomfort experienced.

Body Contribution

In order to gain a more complete insight into the perceptual responses of subjects, an adaptation of the Body Discomfort Scale, was developed. The current research aimed to gain understanding of the areas of the body which the subject perceived they had utilised most in generating the force of the push exertion. An adaptation in the use of the Body Discomfort Map, to highlight areas of the body which contributed to the effort of exertion, as opposed to where discomfort was felt, was used. Feelings of contribution can be associated with strain or fatigue in particular regions of the body, due to the physical nature of the required exertions. Repetitive MMH tasks, frequently witnessed in IDCs, can result in feelings of strain or fatigue, thus the adaptation in the use of the Discomfort Map was felt to be an ideal means of establishing subjective evaluations of an individual's perceived contribution of the body parts contributing to the completion of the task. Previous psychophysical studies have shown no indications of which body parts may be at risk during pushing and pulling, with limited subjective feedback concerning areas of potential injury or concern due to effort contributed in the task.

In unpublished research into body contribution during freestyle isometric pushing and pulling tasks, Cripwell (2004) found that when pushing, subjects felt that the anterior and posterior deltoids contributed most to the effort, with the biceps rated as contributing less to the overall exertion. In addition, all contributions were felt to be greatest when pushing at iliac crest height as opposed to shoulder height, possibly due to the greater forces generated in this position. The pulling responses showed a greater dependence on the musculature of the arms and forearms, particularly at the higher handle height, with some contribution being expressed in the lower limb. However, this may have resulted from a misunderstanding between 'contribution' and 'discomfort'.

The use of perceptual scales, such as the RPE and Body Discomfort, is a subjective method of rating an individual's muscular contributions while performing an activity (Carton and Rhodes, 1985). The reliability and use of any perceptual scales is highly dependent upon the subject being given clear and detailed explanations as well as a thorough understanding of the concept and actual use of the rating scale. Wilson and Corlett (1995) emphasise that persons being evaluated must not try to over or under estimate the ratings, as this could have a significant effect on the overall results.

CHAPTER III

METHODOLOGY

INTRODUCTION

Industrially Developing Countries (IDCs) are often characterised by a limited availability of resources such as equipment, advanced technology and financial funding. Due to the growing awareness worldwide that lifting and carrying are hazardous manual handling tasks, many industries have begun to introduce manual handling devices (MHDs), such as carts and trolleys (Hoozemans **et al.**, 1998). Largely as a result of the high cost of automation, the majority of work performed in IDCs remains manual. MHDs have dramatically reduced the demands placed on the operator as a result of lifting and carrying, but have concomitantly increased the necessity for pushing efforts within the workplace. Increased pushing has introduced a range of new demands on the worker and arguably the situation may not have improved (Resnick and Chaffin, 1995; Schibye **et al.**, 1997; Kingma **et al.**, 2003; Ciriello, 2004). Ultimately there has been little or no reduction in the overall musculoskeletal strain experienced by workers completing the task (Woldstad and Chaffin, 1994). Furthermore, due to haste and/or a potential lack of forethought, many of these devices are poorly designed, and do not account for the human element required to manoeuvre them. These design problems, along with the excessive workloads still predispose the workers to risks of musculoskeletal injury (Dempsey, 1998).

The current research project aimed to gain insight into the impact of load and frequency combinations on the biomechanical, physiological and psychophysical responses of operators during dynamic pushing tasks. To date limited literature exists exploring the role of load and frequency as factors on the aforementioned responses in dynamic pushing tasks. Daams (1993) contended that the lack of standardised methodology in push and pull research has provided additional problems in identifying key factors which influence the individual responses to these tasks. In order to contribute to the effective and efficient performance of any manual task, and to make coherent and valuable recommendations to industry, methodology must be representative of *in situ* conditions. Employing a laboratory-based methodology controls for extraneous factors which may disrupt and influence the results, and factors of importance and interest are highlighted. Acknowledging the need for holistic analysis of any human movement response, this research has abided by the model proposed by Charteris **et al.** (1976), which presents a method of understanding that requires multi-dimensional analyses including the biophysical, psychological, physiological and conceptual domains.

PILOT TEST PROTOCOL

In order to determine the viability and logistical working of the proposed research, extensive pre-pilot and pilot work was undertaken in the Ergonomics Laboratory of the Department of Human Kinetics and Ergonomics at Rhodes University. During pilot work, trials were conducted in conditions that were reflective of the intended testing environment. These preliminary simulations served to refine the testing protocol and establish the suitability of the equipment being used, and the variables being assessed. Volunteers participated in trial protocols wherein load and frequency combinations were tested to establish appropriate combinations for the research. The pilot phase ensured that the researcher was familiar with all equipment and psychophysical scales which would be used during the testing phase of this research.

During pilot studies for this research, the coefficient of friction (COF) of different flooring and its long term suitably were extensively questioned and debated, and 12mm plywood was chosen as the most appropriate flooring after Ciriello (2005), as it has frictional properties similar to many industrial surfaces. The distance to be pushed was set at 14m after repeated trials of all intended conditions. This distance was chosen after reviewing previous push/pull literature (Ciriello and Snook, 1983; van der Beek **et al.**, 2000) as well as investigating the average distances pushed within local industry. A distance of 14m also allowed sufficient distance to differentiate between the forces exerted in the initial, sustained and ending stages of the task. Distance plays a critical role in influencing the time for which sustained forces are exerted, as well as the frequency at which tasks can be performed. It was found that the time it took subjects to complete a push needed to be controlled, in order to ensure that the light/low frequency conditions were performed in the same time as the heavy/high frequency conditions. This was to ensure that all physiological responses were representative of the task, and not influenced by lengthy rest periods between pushes. The speed of push was controlled at approximately 3.6kmh^{-1} for the fourteen metres, through the use of ground markings at regular intervals, and audible cues which marked the time at which the subjects were to reach each marker. This speed was chosen as it represents a manageable walking speed, while challenging the subjects to maintain a suitable work rate.

In addition, different load/frequency combinations were attempted in order to determine which combination would adequately replicate industry, while being manageable within the laboratory environment, given the distance and timing constraints. Through these pilot trials it was established that frequency had no significant impact on the forces exerted by individuals. This was evident in the initial, sustained and ending phases of the push, and it was concluded that force output is a factor of load only. Therefore, in order to ensure truly representative task characteristics while maintaining the structural integrity of the force gauge in use, it was decided that subjects should perform the task at each stipulated load utilising the Chatillon Dynamometer independent of the physiological testing protocol. Thus subjects performed a minimum of two acceptable pushes of each load, at the controlled speed, prior to commencement of the six-minute physiological protocol.

During pilot trials it was established that subjects would need to attend three one-hour testing sessions in order to complete all conditions adequately, without any unnecessary fatigue. During subject habituation all subjects were informed of the requirements prior to attending testing sessions (see Appendix A).

EXPERIMENTAL DESIGN

The current research project aimed to investigate the influence of load/frequency combinations on male subjects' biomechanical, physiological and perceptual responses to dynamic pushing tasks. The biomechanical responses of interest were the initial, sustained and ending forces as well as changes in gait patterns, while heart rate, oxygen consumption and energy expenditure were the primary physiological variables of interest. This led to a research design comprising of nine measured forces and a further nine conditions through the interaction of three different loads and three frequencies.

The conditions tested during the course of this research were:

Table III: Conditions performed during the current study.

	Load		
	200kg	**350kg**	**500kg**
Peak Initial Force	*1*	*4*	*7*
Average Sustained Force	*2*	*5*	*8*
Peak Ending Force	*3*	*6*	*9*

	Load		
Frequency	**200kg**	**350kg**	**500kg**
1 push/ 20sec	*1* *(LF)*	*2* *(MF)*	*3* *(HF)*
1 push/ 40 sec	*4* *(LI)*	*5* *(MI)*	*6* *(HI)*
1 push/ 60 sec	*7* *(LS)*	*8* *(MS)*	*9* *(HS)*

Where: L= light load, M= moderate load, H= heavy load, and F= fast frequency, I= intermediate frequency and S= slow frequency.

Each condition involved subjects performing a dynamic pushing task over 14m on a replica of *in situ* industry flooring at an allocated frequency/load combination for a duration of six minutes. This resulted in 18 minutes of work per 60-minute testing session, which was unlikely to result in excessive strain or fatigue. The six-minute duration was selected in order to allow subjects to reach a physiological steady state condition. McArdle **et al.** (2001) demonstrated that subjects performing aerobic running or swimming tasks reached a level of "steady state" after 3-4 minutes of exercise. However, subjects in those tests were likely to be more familiar with the task, whereas in the current study, subjects would not be as familiar with the test protocol. It was decided that six minutes would allow adequate opportunity for the subjects to reach a steady state condition. Subjects who had reached steady state would do so within six minutes, and those who had not, were unlikely to. Subjects were fitted with the necessary physiological apparatus and then required to perform the load/frequency combination task. Subjects only needed to push the pallet jack and load to the end of the designated area within the time given, where a research assistant was responsible for turning the pallet jack to face the opposite direction before the start of the next push.

Biomechanical measures of force were recorded prior to the commencement of the six-minute protocol while replicating testing conditions. Two acceptable trials of each load were required as no frequency/force relationship was anticipated. This was done in order to limit possible damage to the Chatillon Dynamometer, which had shown signs of potential weakness through repeated trials. In addition, digital video recordings were made during the third and sixth minutes of the six-minute protocol. Although physiological parameters were measured continuously, only recordings made during the fourth and sixth minutes were utilised for the purpose of statistical analysis. Subjects were asked to report on their central and local rating of perceived exertion (RPE) on completion of the third and sixth minutes, while body discomfort and body contribution responses were recorded on completion of each condition.

The loads chosen represent a load below the "biomechanical limit" of 225kg (Resnick and Chaffin, 1995) as well as the 'recommended maximum' of 500kg applicable to industries in South Africa. A 350kg load was chosen to represent loads between the biomechanical limit and the suggested 'maximum' load in industry. The frequencies were determined after extensive pilots as well as a thorough literature review of previous pushing studies that investigated physiological responses (Snook and Ciriello, 1983; Straker **et al.**, 1997). Furthermore, observation and recordings made during numerous industrial visits contributed to finalising these frequencies (Appendix E).

EXPERIMENTAL PROCEDURES

After pilot studies, it was established that subjects involved in testing would be required to attend four sessions each lasting approximately 60 minutes. During the first session subjects would be given a letter of information and the nature and purpose of the research would be extensively detailed to them verbally. After any questions and once subjects were fully aware of the requirements of participation, all participants were required to sign an informed consent form. Thereafter subjects' demographic and anthropometric measures were recorded and all were given the opportunity to familiarise themselves with the Chatillon Dynamometer and pallet jack, as well as with wearing the harness and face mask of the $K4b^2$ ergospirometer. This habituation session served to put the subjects at ease with the task, and to minimise any responses brought on by anxiety or anticipation during actual experimentation.

Each of the next three sessions involved experimentation under three randomly assigned conditions. Two subjects attended each session, and their involvement was alternated in order to facilitate sufficient rest and recovery period between experimental conditions. Subjects had at least one day's break between testing sessions in order to allow adequate recovery.

Prior to the arrival of the first subject for each day, all equipment was warmed up and accurately calibrated. Upon arrival for a testing session, subjects were fitted with a Polar™ heart rate monitor. Once comfortable, the harness and then the $K4b^2$ unit were snugly fitted to the subject's torso. All procedures for correct fitting and adjustment were followed meticulously. Participants were reminded of the different perceptual scales and informed of which conditions they would be completing. Once subjects were comfortable, final air calibration took place and the mouth piece was fitted to the mask. On noting that any anticipatory responses had been controlled for and responses reflected "normal" or reference status, testing began. At the end of each condition, subjects returned to a seat where they were requested to respond to the perceptual scales. Retaining the face mask and heart rate monitor, the k4b^2 unit was fitted to the next subject. The participant was then permitted an opportunity to rest while the second subject for the session completed their trials.

DEMOGRAPHIC AND ANTHROPOMETRIC PROCEDURES AND METHODS

Thirty male subjects between the ages of 18 and 26 volunteered for this study, and were required to be strong, moderately trained and healthy. No medical examination took place and the researcher relied on the subjective self-report of musculoskeletal soundness and health status on the testing days.

Demographic Characteristics

Prior to the onset of experimentation, demographic data were collected from the participants for record keeping purposes. Individual data such as body mass and stature are important in ergonomic research, as these factors are known to influence an individual's ability to perform the required task properly. The interaction of the subject and the equipment being used plays a crucial role in determining the effectiveness and efficiency of task performance, and as such, it is critical that ergonomists take cognisance of the subject's demographic and anthropometric characteristics (Pheasant, 1995; Bridger, 2003). The data collected from each subject are shown in Table IV.

Table IV: **Basic demographic data of subjects (n=30) with mean, standard deviation (SD) and coefficient of variance (CV) values included.**

Measure	**Mean**	**SD**	**CV (%)**
Age (years)	21.87	1.91	8.72
Stature (mm)	1814.53	40.43	2.23
Body Mass (kg)	79.10	8.58	10.85

Body Mass

When performing any pushing task from a stationary position, operators often utilise their body mass to assist in overcoming the object's inertia to create motion. The greater an individual's body mass, the more effective they will be at initiating this movement, with lower forces needing to be exerted by the muscles of the upper limbs. This is an important advantage of a pushing task, as the use of body weight to assist effort minimises the risk of overexertion injuries. Subjects' exerted forces were reported as absolute values (N) as well as relative to body mass ($N.kg^{-1}$).

Oxygen consumption and hence energy expenditure can be influenced by an individual's body weight. Thus, in order to make accurate and pertinent comparisons between subjects of different weights, individual responses were relativised to body weight (i.e. $\dot{V}O_2$ measured in $mlO_2kg^{-1}.min^{-1}$).

The Toledo electronic scale was used to record body mass to the nearest 0.01kg. Subjects were required to remove their shoes and wore minimal clothing. The researcher requested each to stand still, in the centre of the scale facing the wall, with their feet a comfortable distance apart. The readings were recorded manually on the 'Subject demographic and anthropometric data sheet' (Appendix B).

Stature

Stature was recorded in millimetres using a portable Harpenden Stadiometer. Stature is the vertical distance from the floor to the vertex of the individual's cranium. Subjects removed their shoes and stood upright on the Stadiometer base. Arms were pendant at the sides and the head was positioned in the Frankfurt Horizontal Plane. In order to confirm that all subjects were standing as erect as possible, it was necessary to ensure that the heels, buttocks, upper back and posterior surface of the head were all in contact with the vertical support section of the Stadiometer while recording stature.

Stature was an important measure in this study, as stature would directly influence subject's working height. The pallet jack has a maximum handle height of 1175 mm and minimum of 650mm. Due to this constraint, subjects were limited to a stature range of 1750mm to 1900mm, still representative of a large proportion of the male population. According to Williams (1987), stature also plays an important role in determining energy expenditure, through its influence on walking speed.

Anthropometric Procedures

Anthropometry is the human science concerned with body measurements, particularly of size, shape and strength. It is therefore of critical importance to ergonomists, since matching the physical form of the user to the dimensions of a workstation is vitally important (Pheasant, 1995). All measurements were taken on the right hand side of the body. Standardised anthropometric measures were obtained in accordance with the guidelines of Pheasant (1995), which stipulated the precise anatomical landmarks to be utilised in each measurement. In the present study, handle height was controlled by ensuring that all subjects pushed the pallet jack with the handle in the most upright position, which equated to a range falling between elbow and hip height. It has been extensively recognised and acknowledged that handle height should be within the "zone of strength" between hip and elbow height in order to maximise pushing efficiency and effectiveness (Lee **et al.**, 1992; Kumar, 1995; Snook and Ciriello, 1991). It was therefore essential that a measure of the subject's elbow and shoulder height was taken.

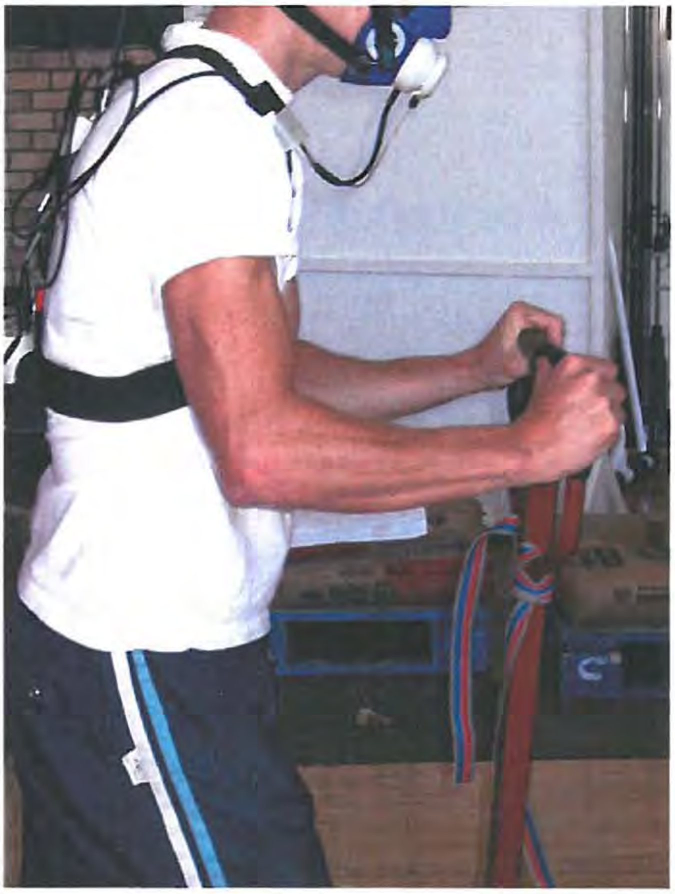

Figure 4: Interaction between desired anthropometry and MHD design allows subjects to exert push forces in positions of optimal strength at approximately elbow height.

Elbow height

Elbow height is the vertical distance from the floor to the radiale, with the subject in the upright position. The radiale is palpated during elbow flexion at 90 degrees, before taking the measurement with the arm hanging freely by the side. The tallest subject had an elbow height of 1125mm, while the shortest elbow height measured was 1024mm. Elbow height represents approximately 62% of an individual's stature, and the pallet jack's handle height of 1175mm falls within the zone of strength for subjects within the required stature range.

Shoulder height

Shoulder height is the vertical distance from the floor to the acromion. The acromion is easily located and palpable in most subjects. Subjects in the lower range of the stature limitations were found to have an average shoulder height of 1360mm, while the tallest subjects displayed an average shoulder height of 1450mm. Shoulder and elbow height measures taken for all subjects are shown in Table V.

Table V: **Anthropometric measures of subjects (n=30), with mean, standard deviation (SD) and coefficient of variance (CV) shown.**

Measure	Mean	SD	CV(%)
Shoulder height (mm)	1412.80	40.84	2.89
Elbow height (mm)	1072.03	31.01	2.89

ETHICAL CONSIDERATIONS

Informed consent

Prior to actual participation in the study, all potential subjects were issued with a detailed 'Letter of Information', clarifying the nature and purpose of the study, as well as the procedures that were to be carried out. Furthermore, on arrival at the first session a comprehensive verbal explanation was provided to each subject. The subjects were welcomed and encouraged to ask questions at any stage during the briefing. At the completion of the explanation and once all queries had been answered, subjects were asked to read an 'Informed Consent' form. The participants, the researcher and supervisor then signed the informed consent form once all parties were satisfied that queries had been adequately responded to in the laboratory. The informed consent forms as well as prior ethical approval from the Rhodes University Research Ethics Committee were prerequisites for the implementation of this study.

Privacy and Confidentiality

All subjects were guaranteed privacy and confidentiality at all stages in the project. Each subject was identified by a personalised code which could not be linked to the subject concerned, except by the researchers involved. The demographic and anthropometric data collected, as well as the measures recorded and digital photos taken, were archived at the completion of the study. The data and pictures were recorded in digital format and stored on a compact disk, with only one copy available. This information was stored in order to allow statistical comparisons as well as reference measures for future researchers interested in the field.

Risk-Benefit to Subjects

The research project was approved as not involving any potentially dangerous side effects or risks to any of the subjects involved by the Rhodes University Research Ethics Committee. All potential risks were immediately reversible, and no long term risk was inherent in the study. The subjects benefited through involvement in the project, as they gained insight into and understanding of ergonomic research within the Department of Human Kinetics and Ergonomics. During testing it was not possible to provide feedback, as the researcher did not want to influence the subjects' subsequent exertions, or other subjects' perceptions. At the completion of the study, all subjects were provided with detailed feedback regarding their results, and the outcome of the study.

TECHNICAL CONSIDERATIONS

Before commencing with any pilot studies or experimentation, it was necessary to ensure that all conditions represented those that are evident in industry. All equipment and environmental factors were assessed to ensure that all possible extraneous factors had been appropriately controlled.

Biomechanical Parameters

Both the equipment used and working environment would impact an individual's ability to optimally perform the stipulated conditions. It was necessary to ensure that all equipment was suited to the experiments underway, and that all factors which could influence the outcome of results were minimised or standardised between subjects. In order to ensure that all biomechanical responses were representative of experimental conditions only, it was critical to control the use of the dynamometer, the quality and mechanical efficiency of the MHD and the flooring on which the task was performed.

Chatillon™ Hand-Held Dynamometer

To gain a measure of initial, sustained and ending forces exerted by the subjects during the course of the dynamic pushing tasks as an indicator of the biomechanical stresses placed on the body, the Chatillon™ FCE-500 Hand-Held Dynamometer (Chatillon, Technitrol Company, Greensboro, NC) was used. The FCE Series utilised in the current study is accurate to within 0.25% at full scale, with a load capacity of 250kg of force. The forces exerted on the dynamometer are indicative of the strength requirements needed to initiate movement of the pallet jack, sustain that movement and ultimately bring the load to a complete stop. The FCE-500 Chatillon Hand-Held Dynamometer is capable of measuring axial tensile and compressive forces, thereby allowing researchers to measure an individual's capacity to achieve and maintain a force exertion, and to obtain quantitative data on an individual's ability to perform the task. This information was critical to this study's aim of isolating and quantifying the forces required in each stage of a pushing task: initial, sustained and ending.

The Chatillon Dynamometer was used in conjunction with Nexygen DF Series Software. The dynamometer connected directly to a laptop computer through the required COM port. This software package displayed and recorded all results numerically and graphically, and allowed the researcher to control the settings from the computer without interfering with the dynamometer itself. The Nexygen Software facilitates presentation of all results in Microsoft Excel. Required information was recorded approximately every 0.3 seconds, and automatically saved, before being exported to Microsoft Excel. Prior to the collection of force data, the Nexygen software was set up according to the test requirements, using the programme's test configuration. Due to the rate at which data were accumulated, and the frequency of the task, it was deemed sufficient to record the pushing responses for two complete trials of each load. Therefore a total of two measures were recorded per load, which is greater than any previous pushing and pulling research has used (eg. van der Beek **et al.**, 1999; van der Beek **et al.**, 2000).

A laptop computer running the Nexygen software was placed carefully onto the pallet jack and connected to the Chatillon Dynamometer, which served as the pallet jack handle for all biomechanical measures. The laptop computer was transported on the pallet in order to ensure that the connection remained intact, as no telemetric measurement was possible. This meant that it was necessary for the laptop to be securely fixed to the pallet at all times. The mass of the laptop computer (kg) was incorporated into the load being moved.

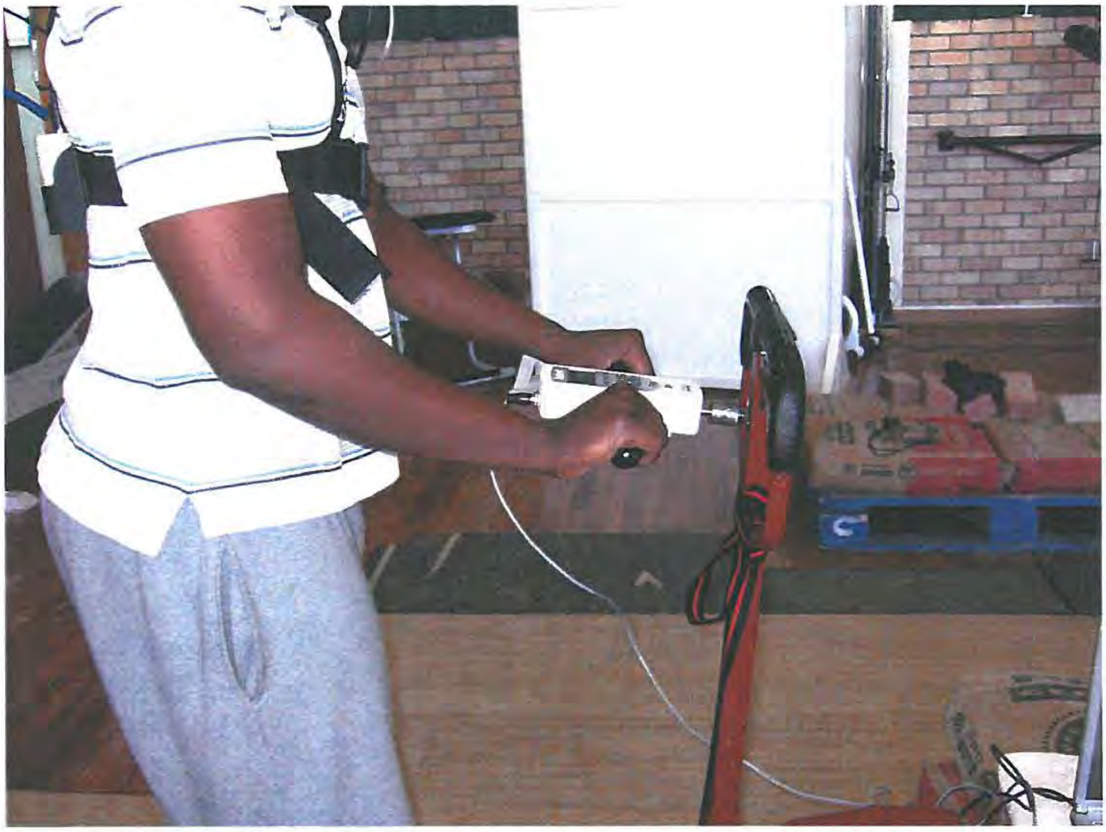

Figure 5: Subject utilising Chatillon™ FCE-500 Hand-Held Dynamometer.

Flooring

A MHD which has been correctly designed and is used according to specifications is effective at transferring heavy weights with pushing forces that are acceptable to the majority of both male and female workers (Straker **et al.**, 1996; Ciriello, 2004). This, however, assumes that the coefficient of friction (COF) between the flooring and the shoes worn is high enough to sustain the physical output capabilities of the workers, as well as their balance. The COF forces are dependent upon the interaction between the floor and the feet, in order to generate enough friction to allow an individual to maintain their posture, while still exerting the necessary forces. Subjects in this study were required to wear the same sports trainers with suitable rubber soles to all testing sessions, in order to maintain the COF within acceptable ranges. In the present study, the flooring consisted of 2440mm long, 1220mm wide and 120mm thick interchangeable untreated plywood panels which ran for a distance of 17m. This flooring was chosen as it has been shown by Ciriello **et al.** (2001) and Ciriello (2005) to achieve COF values that are higher than the recommended values for safe floors (0.4 – 0.6 COF), while still representing the COF found in floors common in industry. In addition, this flooring has been commonly used in previous pushing and pulling research (Ciriello, 2005).

Figure 6: Plywood floored runway used to replicate coefficient of friction evident in flooring used in industry.

Industrial Pallet Jack

A manual hydraulic pallet jack, commonly used in industry, fitted with new front and rear castors/wheels was utilised in this study. The pallet jack weighed 78kg when unloaded. The handle of the pallet jack was modified to allow for the Chatillon Dynamometer to be fitted to the pallet jack, at the desired handle height, thereby eliminating the need for the subjects to control the position of the handle while performing the task. The pallet jack arm was secured in the upright position through the use of luggage tie-downs. This ensured that when subjects pulled back on the handle in order to bring the pallet jack to a stop, the handle stayed in the upright position and so all forces were exerted horizontally, and the handle never gave way. No further adjustments were made to the pallet jack. All subjects were provided with the opportunity to familiarise themselves with pallet jack operation, although no action besides direct pushing and stopping of the pallet jack was required. This meant that all recorded data was limited to a pure pushing only task. Subjects were not required to exert themselves additionally by turning the pallet jack before the next push, a movement which could not be classified as a pure horizontal pushing motion.

Digital Video Camera

Within Industrially Developing Countries (IDCs), MMH poses substantial risks of low-back musculoskeletal injury, due to the mass of the object being manipulated, awkward postures assumed by workers, schedule pressures driven by time constraints and often harsh environmental conditions (Hess **et al.**, 2004). Grieve and Pheasant (1981) defined postural stress as the mechanical load on the body by virtue of its posture, which is the orientation of body parts over time. Task-induced stress depends on the mechanical effort needed to perform the task. The alignment of the body parts must be maintained at all times in order to remain continuously stable, and it is this maintenance, during work-related tasks, that exacerbates the stress (Bridger, 2003). Posture is therefore a key consideration in any assessment of risk.

In order to record the postures of subjects during the pushing task, as well as carefully and accurately monitor the subjects' gait patterns during the tests, digital video recordings using a Panasonic NV-GS 35 digital video camera analysed through Silicon Coach PRO 6 software (SiliconCoach Limited, 2002) was utilised. The camera was positioned at 7 metres, 2.5 metres away from the track at 90 degrees to the walkway. Recordings for the duration of one push after three and five minutes were used in this study.

Physiological Parameters

The quantity of energy generated by the body during rest and muscular effort can be accurately determined using indirect calorimetry (McArdle **et al.**, 2001), which is far more practical for ergonomists interested in energy expenditure during occupational tasks than direct calorimetry. Indirect calorimetry is the measurement of energy expenditure via the measurement of the volume of oxygen consumption and carbon dioxide production (Littlewood **et al.**, 2002).

Cosmed K4b^2- Portable Spirometer

The Cosmed K4b^2 is a portable metabolic online system designed by Cosmed to measure gas exchange on a breath by breath basis. The K4b^2 is an open-circuit method of measuring oxygen consumption during which individuals inhale ambient air with a constant composition of 20.93% Oxygen, 0.03% Carbon Dioxide and 79.04% Nitrogen. Its technology enables the exploration of physiological responses in the field or laboratory for both short and long term events. The K4b^2 accurately measures over 30 physiological parameters including $\dot{V}O_2$, VCO_2, Heart Rate and Ventilation rate. Research into the accuracy and reliability of the Cosmed K4b^2 by Littlewood **et al.** (2002) and Duffield **et al.** (2004) concluded that the K4b^2 demonstrated accuracy, satisfactory reliability and good repeatability, provided that the K4b^2 was used to measure the cost of activity and not resting energy expenditure. Energy expenditure in kilojoules per minute was calculated by multiplying absolute $\dot{V}O_2$ by 20.1 ($ml.min^{-1} \times 20.1 = kJ.min^{-1}$). Kilocalories per minute were calculated by dividing the kilojoules per minute by 4.186 ($kJ.min^{-1} \div 4.186 = kcal.min^{-1}$).

Each subject was required to wear a correctly sized facemask from which cabling led to the portable unit containing oxygen and carbon dioxide analysers, as well as a sampling pump, UHF transmitter, barometric sensors and electronics. Powered by a battery, this portable unit was fixed to the subject's back via a harness. A receiver unit received the telemetrically transmitted data from the portable unit and allowed these data to be displayed on a laptop computer containing the appropriate software. An analysis of the difference between the exhaled air and the ambient air reflects the body's use of oxygen and release of energy.

Prior to experimentation it was necessary to conduct the K4b^2 room air calibration, gas calibration and flowmeter calibration. Room air calibration required sampling room air in order to update the O_2 and CO_2 analysers. Reference gas calibration required sampling a gas with a known composition, and flowmeter calibration was executed using even inspiratory and expiratory strokes from a three-litre syringe.

Figure 7: K4b^2 Ergospirometer in use, securely fastened to the subject's back.

Heart Rate Monitoring

In order to attain a measure of cardiac strain, Polar™ Heart Rate Monitor chest straps were used. The Polar coded transmitter was fitted with an elastic strap at the level of the inferior border of the pectoralis muscle in line with the left ventricle of the heart, slightly to the left of mid-centre of the chest. The telemetric strap measures the heart's electrical activity. The K4b^2 is fitted with a receiver unit which automatically measures and records the individual's heart rate responses through the K4b^2

software package. It was essential that good contact between the telemetric strap and the skin was maintained, and this was facilitated by moistening the conductive electrode straps with water or electro-conducting gel.

Before any experimentation took place, a reliable reference heart rate was recorded and used as a reference heart rate. The volatility of heart rate responses due to changes in environmental conditions, anticipation and movement renders heart rate a very sensitive measure. In order to achieve this reference heart rate, subjects were required to sit quietly without talking until heart rate stabilised.

Psychophysical Parameters

Perceptual scales are used to assess the well-being of human operators during the completion of an activity and to gain insight into and an understanding of the individual's subjective perception of the task at hand (Wilson and Corlett, 1995). The individual's perceptual responses to physical activity reflect the personalised reactions to the task's demands, aiding the researcher in understanding the holistic demands of dynamic pushing at different load/frequency combinations.

Rating of Perceived Exertion (RPE)

The RPE scale, proposed by Borg (1970), is commonly used as a subjective measure of exertion during exercise testing (Noble, 1982). Traditionally used in the field of exercise science, ergonomists interested in the physiological impact of Manual Materials Handling (MMH) utilise it during aerobic testing of workers performing manual handling tasks, to monitor participants' feelings of effort during the protocol (Noble, 1982). Subjects rate their perceived levels of exertion during the task, on a scale from 6 to 20, corresponding to heart rates of 60 to 200 beats per minute. The RPE scale is simplistic, yet reliable, since it displays a strong relationship with exercise workload and heart rate (Noble, 1982).

RPE responses can be divided into those representing the workings of the cardiopulmonary systems, known as a central RPE, and those which represent the working musculature of the body, known as local RPE. During this study, local RPE was limited to a rating of upper extremity muscular strain. Individual RPE responses, both local and central, were recorded at minute 3 and minute 6. Subjects were asked to give their central rating first, followed by their local rating.

Body Discomfort Map

The concept of the Body Discomfort Map and Rating Scale (BDS) was proposed by Corlett and Bishop (1976), and is now seen as a valuable means of examining an individual's muscular discomfort during any physically demanding activity. Repetitive MMH activities, frequently observed in IDCs, often result in strain or discomfort, therefore the BDS is an ideal method of gaining subjective insight, and of evaluating perceived discomfort during the execution of the task (Carton and Rhodes, 1985).

Due to individual variability, ratings of discomfort may vary significantly amongst individuals, and the reliability of the BDS is dependent upon a clear and thorough understanding of its concept and application (Wilson and Corlett, 1995). The Body Discomfort Map is presented as an anterior and posterior drawing of the body, divided into 27 clearly identifiable sections. Below the drawings is a scale rated from 1 to 10. Subjects are required to point out the area of the body which they feel experienced the most discomfort and then rate the intensity of that discomfort. This is followed by a second and if need be third site identification and rating.

Tasks involving awkward or uncommon postures tend to have the greatest discomfort rating (Straker **et al.**, 1997). Similarly, high frequency tasks are consistently rated higher in discomfort than the same task performed at lower frequencies (Straker **et al.**, 1997), presumably due to muscular fatigue. In the current study, body discomfort ratings were recorded manually at the completion of the condition performed.

Body Contribution Map and Rating Scale

In order to develop a means of obtaining psychophysical feedback from the subjects regarding the region of the body they felt contributed most to their effort during dynamic pushing, a Body Contribution Map and Rating Scale (BCS) was used. The Body Discomfort Scale (BDS) (Corlett and Bishop, 1976) was adapted in title as well as the degree of contribution attributed to that body part.

The BCS was clarified during the verbal explanation of the research study, and it was meticulously explained that the map, although similar to a BDS (familiar to selected subjects) was not a discomfort rating, but rather a contribution rating. It was also emphasised to each subject that when recordings are taken, that they point out the area of contribution, as opposed to voicing it, to minimise influence on other subjects' responses. Once an area had been identified by a subject, they were asked to objectively rate the extent to which that area contributed to the maximal exertion, on a scale from 0 to 10, where 0 represented no contribution, and 10 maximal contribution. The BCS responses were recorded upon completion of each condition, and subjects were then requested to point out the three main contributing areas, and rate them separately.

STATISTICAL PROCEDURES

Results of pilot studies were tested for power, in order to establish whether the independent variables selected had been done so with a strong possibility of establishing a significant finding between dependent results. For all physiological variables of interest (HR, $\dot{V}O_2$, EE) this prospective power analysis reflected an average power value between all nine conditions of 0.8, deemed suitable by Cohen (1988). Retrospective power analysis of all physiological responses returned an average effect size of 1.07 (±0.36), corresponding to a power value of approximately 0.95. For all force measures (initial, sustained and ending) the retrospective effect size analysis returned an average value of 1.23 (±0.76), indicating power in excess of 0.99.

Analyses of data were carried out using the STATISTICA 7 (Statsoft Inc, 2005) computer programme. Initially all data were analysed descriptively, in order to test symmetry and obtain measures of means and standard deviations of each condition.

A T-test was carried out between all physiological responses recorded during the fourth and sixth minutes, with the confidence level set at 99%. This test showed that no significant difference existed and hence a steady state condition was reached. The physiological responses from the final minute were therefore used for all statistical analyses.

The sample used in this study comprised 30 male subjects, randomly sampled from the Rhodes University population, and thus parametric statistics were run on the responses. The statistical responses were all tested at the 95% level of confidence, meaning that the criterion for significant difference was set at $p \leq 0.05$ for each of the hypotheses. For hypotheses 1c, 2 and 3, initial 2-way analysis of variance (ANOVA) was conducted to establish whether in fact a load or frequency effect existed. Thereafter, detailed 1-way ANOVAs were run on all conditions to establish significant differences between all conditions.

CHAPTER IV

RESULTS AND DISCUSSION

INTRODUCTION

From an ergonomics perspective, occupational injuries and incidents are mainly due to improperly designed tasks and workplaces. Poor workplace design causes faulty judgement, more errors, higher accident rates, increased sick time and lower productivity, which all impact on a country's economy. The reduction of such incidents, frequently associated with manual materials handling (MMH) is one of primary concern to ergonomists and to managers alike (Jung and Jung, 2001).

As MMH tasks have been shown to place excessive demands on the worker (Ayoub and Mital, 1989), improving the compatibility between the task and the human operator is crucial. Despite recent technology transformations, many workers are still required to handle jobs manually, often resulting in significant injuries, and even fatalities (Khalaft **et al.**, 1999). The leading type of health hazard that results from MMH work is lower back injuries, and Capodaglio **et al.** (1997) suggest that manual lifting, lowering, pushing and pulling are occupational risk factors that need to be contained within safe limits. Lifting has been historically cited as a significant risk factor for occupationally-related low-back disorders (Marras **et al.**, 1995). Industry has responded to this risk by modifying the workplace in order to decrease lifting and carrying tasks, often replacing them with pushing and pulling exertions (Granata and Bennett, 2005). However, there is epidemiological risk associated with pushing and pulling too, and it is expected that this injury rate, albeit differing, will continue to increase in response to the trend toward a growing number of push and pull-related tasks in the workplace.

Traditionally manual tasks have been assessed in terms of biomechanical, physiological and psychophysical strain placed on the workers (Dempsey, 1998).

Despite the fact that over 50% of tasks performed in industry require pushing or pulling exertions (Baril-Gingras and Lortie, 1995), the biomechanics of pushing and pulling exertions remain poorly understood (Granata and Bennet, 2005), and the physiological impact neglected (Hoozemans **et al.** 1998), since early studies in the 1960s and 1970s of Williams **et al.** (1966), Wyndham and Heyns (1967), Haisman **et al.** (1972), Haisman and Goldman (1974) and Datta **et al.** (1978 and 1983).

The objective of the current research was to examine the biomechanical, physiological and psychophysical responses of male operators to changes in load/frequency combinations during a dynamic pushing task. The investigation aimed to identify load and load/frequency combinations at which all responses were optimised, in order to provide some basic guidelines for the safe use of dynamic pushing tasks within industry in developing countries. A total of nine different experimental conditions were achieved through the combination of three loads and three frequencies.

FORCE EXERTION

Task performance during each phase of the task needed to be controlled in order to reduce inter-subject variability. In this respect, walking speed was delimited to approximately 3.6km.h^{-1}. The pattern of response was similar for all loads conforming to that described by van der Beek **et al.** (1999) who stated that "a typical pattern" involves an initial peak force, followed by a smaller sustained force to maintain movement and finally a negative peak force to decelerate and stop the object. The lack of standardised methodology in push/pull research has been argued to be a major reason for uncertainty in scientific findings. In a review of pushing and pulling research, Todd (2005) concluded that:

> "further research into this field is imperative in order to create a clearer understanding of the forces involved in pushing and pulling in industry in order to make recommendations that are likely to maximise the efficiency of the human operator" (pp. 8).

Achieving consistent force output patterns representative of an industrial pushing task was thus fundamental to the current research.

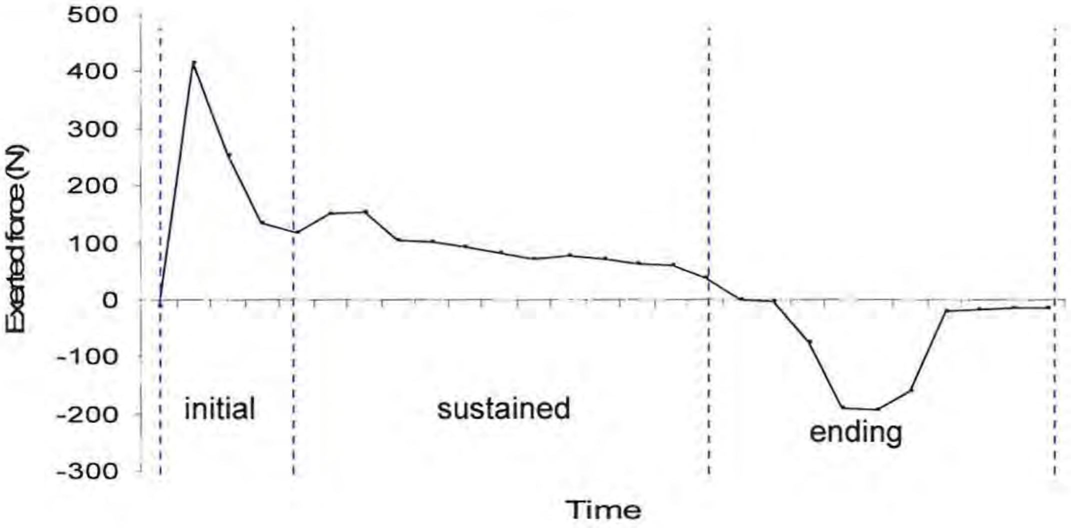

Figure 8: Typical curve of the total exerted force in pushing, identifying the initial, sustained and ending phases.

Under the constraints of the experimental conditions, the subjects recorded force output patterns similar to that depicted above for all loads, highlighting the initial, sustained and ending phases characteristic of a pushing task. Differences were only noted in the actual force amplitude during each stage and not in the pattern presented.

It is clear to see in Figure 8, where the peak initial and peak ending forces were measured, peak ending forces were recorded as negative values owing to the fact that the force was applied in the opposite direction to that in which the pallet jack was moving. Ending forces for this dynamic 'pushing' task were therefore pulling forces, since the forces were exerted towards the operator's body. For the purposes of statistical and meaningful comparisons, all forces are reported as absolute values. This analysis follows that of Jansen **et al.** (2002) who described the peak force during the initial phase and during the ending phase as being represented by the peak values at the beginning and at the end of the curve. In Figure 8 the area utilised to calculate the average sustained force for each load is shown. The sustained forces were defined as the mean values of the force between peak initial and peak ending.

Through the control and standardisation of methodology it becomes possible to isolate each phase of the task for thorough analysis. The current research involved isolation of the initial, sustained and ending phase of the task, despite prior research generally being aimed at the assessment of initial exerted forces to accelerate an object and the sustained exerted forces to maintain a more or less constant velocity (Snook, 1978).

Individual Variation

Evident from the wide ranging coefficient of variation shown in Table VI, there is considerable inter-individual variability in the force-generating responses. Despite controlling the speed, the task was 'freestyle' in nature and individuals responded in a broad variety of ways. The greatest range in forces exerted (262.8N) occurred in the ending phase while pushing the 500kg load. The initial and ending forces exerted for each load were particularly dependent on the technique used by the subject (for example bringing the pallet jack to a stop smoothly or abruptly).

Table VI: Mean peak forces (N) exerted in the initial (PI) and ending (PE) phases, as well as the average sustained (AS) force, for all three loads.

	200kg			350kg			500kg		
	PI	AS	PE	PI	AS	PE	PI	AS	PE
Mean	212.8	50.0	137.8	293.7	89.2	202.2	366.3	125.6	246.4
SD	45.3	8.8	44.4	50.8	14.2	55.7	47.0	17.6	58.1
CV	21.3	17.5	32.2	17.3	15.9	27.6	12.8	14.0	23.6
Min	113.3	26.6	53.7	200.2	67.2	102.3	274.5	88.0	111.0
Max	315.3	64.8	264.2	387.8	115.5	357.4	484.7	156.3	373.8

Where: SD = standard deviation, CV = coefficient of variation, Min = minimum force recorded,
Max = maximum force recorded.

As the mass of the MHD increased, so too did the mean peak forces. The PI force increased from a mean of 212.8N to a mean of 366.3N from the lightest to the heaviest load. The PE force followed the same trend but with significantly lower responses ranging from 137.8N to 246.8N. Expectedly therefore, the AS force also increased significantly with increasing load. However, despite these expected differences, the pattern of response was similar for all loads.

Subjects who attempted to overcome the pallet jack's inertia with an immediate push recorded high peak initial forces, while those who gradually applied pressure achieved movement with lower force exertion. As load increased so variation decreased, as is evident in peak initial (PI) forces where the variation drops from 21.3 at 200kg to 12.8 at 500kg.

Variation in the sustained phase is minimal as the subjects were only required to control the pallet jack over the set distance. This indicates that the sustained phase of a controlled pushing task is likely to elicit similar force output responses from all operators, regardless of differences in morphology, anthropometry and technique. It can be seen from the results of Table VI that the peak forces recorded in the initial and ending phases of the task are dependent not only on load moved but also on technique, exposedt through the high coefficient of variation and standard deviation. Average sustained forces are therefore more dependent on the load moved, and the design of the MHD than on the technique used.

Despite the value and knowledge attained by isolating the three phases and the associated forces for each load from the dynamic task, it is of imperative interest to the current study to understand and explore the differences between all nine forces, and also the inter-relationships that arise between them.

Combination Responses

The mean peak initial (PI), average sustained (AS) and peaking ending (PE) forces recorded while pushing loads corresponding to 200kg, 350kg and 500kg were of primary biomechanical interest in the current study.

Table VII represents the mean forces achieved at each phase of the dynamic pushing task for all three loads. The lowest force requirements were sustained forces of 50N at 200kg and the highest was 366.3N for 500kg initial forces. The mean peak initial force achieved when pushing a load of 200kg (212.8N) does not differ significantly from the mean peak ending force required of a 350kg load (202.2N). In addition, the mean peak forces required to bring a 200kg pallet jack to a stop are not significantly different to the average sustained forces required to keep a 500kg pallet jack in motion.

Table VII: Mean forces (with SD in brackets) exerted at each of the three stages of the dynamic pushing at all three loads.

Load	Peak Initial (PI)	Average Sustained (AS)	Peak Ending (PE)
200kg	^{1} 212.8 (45.3) ^{A}	^{2} 50.0 (8.8)	^{3} 137.8 (44.4) ^{B}
350kg	^{4} 293.7 (50.8)	^{5} 89.2 (14.2)	^{6} 202.2 (55.7) ^{A}
500kg	^{7} 366.3 (47.0)	^{8} 125.6 (17.6) ^{B}	^{9} 246.4 (58.1)

$^{A, B}$ Indicates **no significant difference** ($p<0.05$) between the exerted forces; all other forces were significantly different.

These are important findings, as it illustrates the importance of load weight and task demands in the consideration of biomechanical limiting factors. Authors such as Snook and Ciriello (1991), Mital **et al.** (1997) and Ciriello **et al.** (1999a) have all advocated that "the biomechanical design criterion is not the limiting factor" in pushing tasks, and that sustained forces are not likely to contribute to traumatic injury. In addition, van der Beek **et al.** (1999) and Hoozemans **et al.** (2004) argue that the initial forces are of primary interest in the development of musculoskeletal disorders while no research has considered the peak ending forces. The similar responses found between initial (200kg) and ending (350kg) forces indicate that ending forces may also add to acute or traumatic muscular disorders or fatigue. Forces of this magnitude are likely to contribute towards muscular fatigue or disorder development, regardless of whether they are exerted in the initial, sustained or ending stages, and thus each phase of the task deserves further attention as to the true biomechanical impact on the human operator.

Close inspection of the results shown in Table VIII confirms the importance of average sustained forces in assessing the demands of any dynamic pushing tasks. Understanding the relationship between the initial, sustained and ending forces provides useful insight to the extent to which the forces challenge the musculature of the body. The ratio between PI forces, AS forces and PE forces are shown in Table VIII.

Table VIII: Ratio between peak initial (PI), average sustained (AS) and peak ending (PE) forces at each load.

Load	Peak Initial (PI)	Average Sustained (AS)	Peak Ending (PE)
200kg	4.26	1	2.76
350kg	3.29	1	2.27
500kg	2.92	1	1.96

It is clear to see from Table VIII that as the load increases, so the ratio between average sustained force and peak initial, and average sustained and peak ending force decreases. Peak initial forces drop from 4.26 times average sustained forces at 200kg, to 2.92 times sustained forces at 500kg, while the peak ending forces drop from 2.76 to 1.96 times greater than the sustained force. Consideration of the sustained forces as an important biomechanical measure in pushing tasks thus increases as the load increases, since sustained forces increase as a percentage of both peak ending and initial forces. It is critically important for future research and industry to take cognisance of the finding that at heavy loads it is imperative not only to consider the peak initial forces, but also the sustained and ending forces.

Initial Forces

Forces exerted in the initial stage of any pushing task are likely to be the highest, since overcoming the object's inertia as well as the frictional properties between object and floor, and beginning movement will require more force, than sustaining the consequent movement. This situation is therefore relatively static in nature, and so provides the potential for immediate musculoskeletal disorders by exceeding the capacity of the soft tissue structures required to generate the force. If the task is repeated over the long-term, the chance arises that repetitive static loading of the musculature, particularly the smaller muscles of the upper extremity, could result in more chronic long-term fatigue and ultimately injury.

The initial forces required to set the pallet jack in motion are only exerted in approximately the first three to five seconds of the task performance. The short duration and expected high intensity creates the possibility for acute musculoskeletal injury and thus the peak force required/attained is of interest to the current study. Van der Beek **et al.** (1999) argue that for initial and ending forces only the peak forces, to accelerate or decelerate the MHD, have to be assessed.

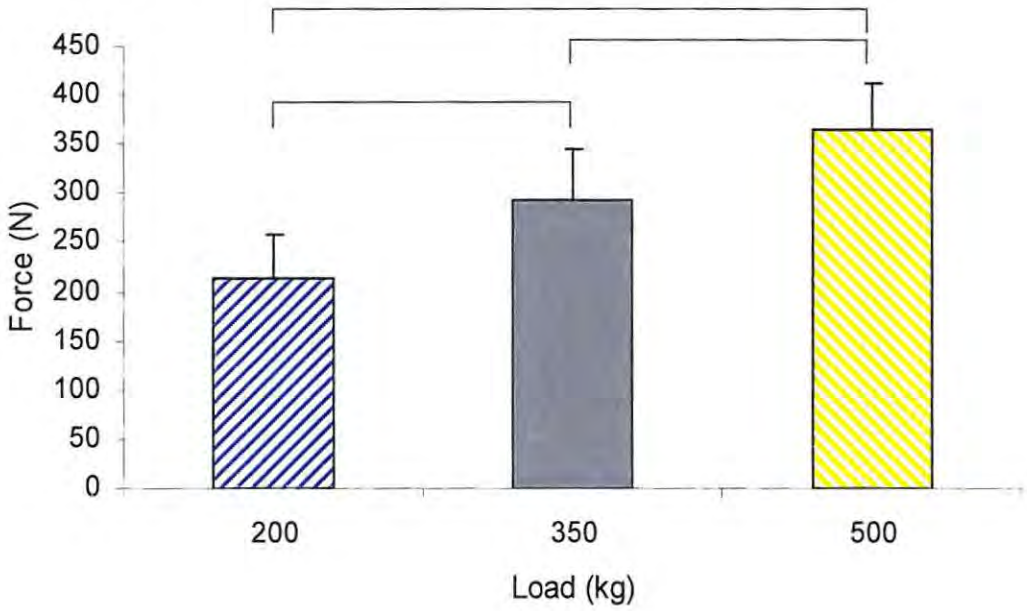

Figure 9: Mean peak initial forces (PI) exerted at each load, with SD shown.
Longitudinal bars link loads with significant differences (p<0.05).

The peak initial forces exerted at each load were significantly different from each other (p≤0.05), indicating that as load increased so did the force output. An increase in load from 200kg to 350kg (75%) required peak initial forces to increase by 38%. Interestingly, when the load increases from 350kg to 500kg (42.8%), the average peak initial forces required to set the object in motion (366.3N) were only 24.7%

higher than at 350kg (293.7N). Thereafter it is evident that a 150% increase in load required a 72% increase in exerted forces. Similar findings have been reported by van der Beek **et al.** (1999), Al-Eisawi **et al.** (1999) and Laursen and Schibye (2002).

Load weight is the foremost task factor in pushing due to the close connection with the subsequent force requirement (Jung **et al.**, 2005). Haslam **et al.** (2002) and Jansen **et al.** (2002) both reported a linear increase in force required to set an object in motion, as the load of the trolley increased. Figure 9 displays the mean peak initial forces exerted for each load during the current investigation, illustrating clearly the increase in required initial force in order to set heavier loads in motion.

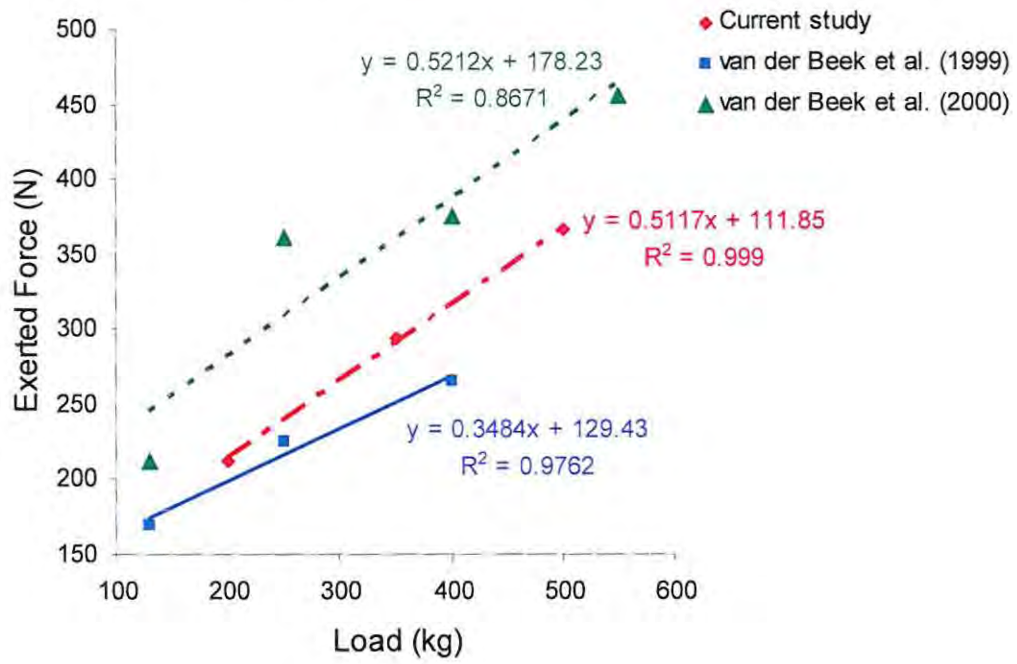

Figure 10: Relationship between load and peak exerted forces in the initial phase of the task.

The current research established a linear relationship between load and initial exerted forces with a high correlation coefficient. Achieving a linear relationship of this nature is an important finding as it opens up the possibility of predicting the initial exerted forces that will correspond to loads pushed under conditions similar to those used in the current study. Industry would benefit from the ability to predict and thus control the extent of the forces required to set a pallet jack in motion, and therefore limit the chances of overexertion injuries occurring. Figure 10 further demonstrates that not enough focus has been placed on the relationship between exerted forces and load, as only two prior studies reported sufficient data to generate a relationship (van der Beek **et al.**, 1999; van der Beek **et al.**, 2000). Although the correlation achieved by van der Beek and colleagues is not as high as in the current study, any correlation above 0.80 still demonstrates a strong positive relationship between load and initial exerted forces. One reason for the possible lower correlation between load and initial forces exerted in the van der Beek **et al.** (2000) study and the current study could be the variability in their results, indicated by coefficient of variations in excess of 30% for all loads, likely attributable to the small sample size of four.

The guidelines of Mital **et al.** (1997) are often used to evaluate push and pull forces in terms of maximum acceptable forces in the initial phase. Distance plays a very limited role in determining peak initial forces, as the forces are exerted in order to initiate the movement desired. In fact, until the peak initial force required to start movement is attained, no movement is witnessed because initial inertia has not yet been overcome. Distance is therefore more likely to play a role in the sustained forces exerted. Ferreira (2004) refers to European legislation regarding manual handling at work (HSE L23, 1998), stating that numerical guideline figures are based on scientific research and practical experience.

The guidelines proposed by Ferreira (2004) and Jung **et al.** (2005) suggest maximum initial forces of 245N and 225N respectively. These limits were exceeded by both the 350kg and 500kg loads. The guideline data presented by Mital **et al.** (1997) may not be applicable in IDC industries where the psychophysical limitations have not been derived. Instead, industry would respond better to guidelines that equate specific loads to a specific range of exerted initial forces dependent on an individual's anthropometry, and limitations to the extent to which forces can be exerted before any musculoskeletal damage can occur, in both the short and long term. Establishing effective guidelines therefore requires further extensive investigation into the required peak initial forces at a wider range of loads, and for a broader cross-spectrum of individuals (stature, mass and gender), as well as changing conditions (handle height, COF). Further, joint loading capacities must be examined at these forces to determine the extent of possible musculoskeletal damage that could occur.

Sustained Forces

Once in motion at a constant speed, the force requirement is generally lower for all loads. At this velocity the forces resisting movement are restricted to friction and physical interference, and momentum tends to keep the MHD in motion. In the current study, the average sustained forces, shown by Figure 8, were calculated as the average force exerted in the forward (pushing) direction, between the initial and ending phases of the task. As sustained forces are exerted over a period of time, it is important to report not only the level of the forces exerted but also the duration. In the current study, sustained forces were exerted for approximately nine seconds, out of a total of fourteen seconds for the full exertion over fourteen metres.

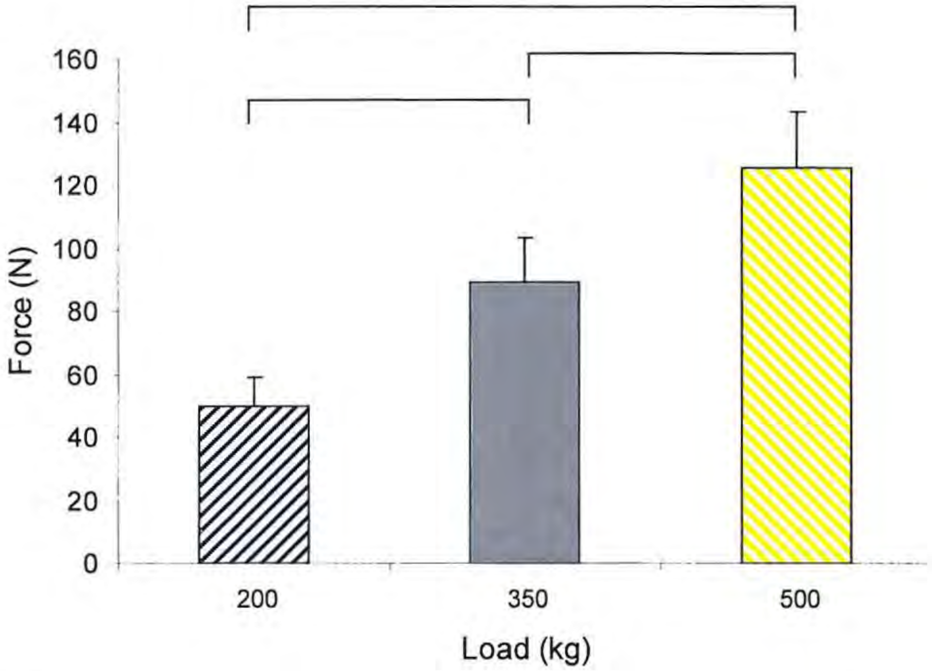

Figure 11: Average sustained (AS) forces exerted at each load, with SD shown. Longitudinal bars link loads with significant differences ($p<0.05$).

Figure 11 clearly shows the increase in sustained forces as the mass of the pallet jack and load increases, highlighting the importance of load mass as an influencing factor in potential overexertion injuries. Significant differences ($p<0.05$) were found between the exerted forces for each load, indicating that significantly more force was required for the higher loads than for the lighter loads. Further investigation reveals that a direct linear relationship exists between load mass and sustained exerted force. A 75% increase in load from 200kg to 350kg, brings about a 78% increase in necessary sustained force; while an increase of 43% between 350kg and 500kg brings about a similar (41%) increase in the required sustainable forces. Similarly, the 150% increase in load between 200kg and 500kg resulted in a 150% increase in the sustained forces.

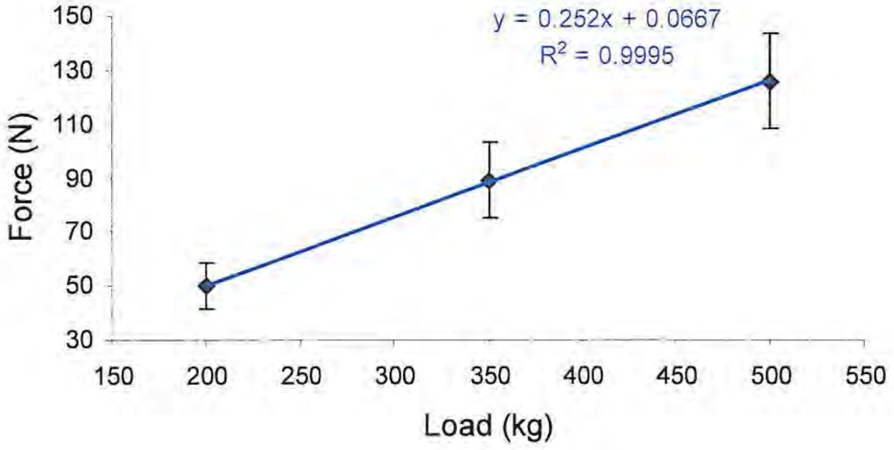

Figure 12: Linear relationship between average sustained (AS) force and load.

Figure 12 demonstrates the direct linear relationship between average sustained forces and load, clearly showing a high correlation (0.9995). This result confirms the importance of research into all three stages of any dynamic pushing task, and not only the stages in which it is expected that musculoskeletal injury will occur. The finding presents useful information to ergonomics practitioners within the workplace, as it allows for the average sustained forces to be predicted from the weight to which the pallet jack is loaded.

During the current research, the sustained forces represented 2.6% of the load, for each of the three loads (200kg, 350kg and 500kg). Therefore changes in load resulted in equal increases in force requirements, regardless of the load. This finding provides an important predictive capacity for the sustained forces of loads different to those used in the current study, but pushed under similar conditions. Van der Beek **et al.** (1999) investigated the initial, sustained and ending forces involved in pushing a four-wheeled cage, loaded with weights of 130kg, 250kg or 400kg. In their study, the resulting sustained forces represented a range of between 3.4% and 4.7% of the actual load. The differences may be attributed to walking speed. During this investigation walking speed was controlled, and therefore the sustained forces are representative of the load, with as many extraneous variables as possible being minimised.

Knowledge of the average sustained pushing forces associated with each load is important, as it is these forces that are going to have predominant bearing on an individual's energy expenditure and fatigue, since prolonged periods of force application increases fatigue and reduces the amount of force that can be sustained, along with the number of people who are capable of performing the task (Snook and Ciriello, 1991; HSE, 1998). Significant differences ($p<0.05$) arose between all loads, indicating that load weight has a significant impact on the required sustainable forces.

The guidelines of Mital **et al.** (1997) provide the most comprehensive cover of pushing task limitations. Understanding what forces are required to be sustained for what load would be invaluable to industry. Mital **et al.** (1997) recommended that no more than 88N be sustained over a distance of 7.6m, while the guidelines of the HSE (2004) state 98N and Jung **et al.** (2005) suggest 112N is the upper limit acceptable for sustained force in a pushing task. Based on the present results, loads above 500kg should not be pushed in industry, as sustained forces were 125.6N. It is common knowledge that pallet jacks in all industries around the world are frequently loaded well in excess of 500kg. Although this limit would mean that both the 200kg and 350kg load would have been acceptable, other factors (such as friction and maintenance) must be considered. Taking cognisance of all perspectives, especially in developing countries where worker characteristics are substantially different from their western counterparts is crucial. The forces exerted in the current study showed that the pushing and pulling guidelines are most probably exceeded at the workplace on a regular basis.

Sustained forces are to be expected to change dramatically too if they are required to be exerted on surfaces of different gradients. Pushing a MHD up a positive gradient will require sustained forces that may even exceed the initial forces required to set the object in motion (Desai, 2006). Similarly, pushing down a negative gradient could require sustained forces to be exerted as pulling forces, again possibly even exceeding the initial forces. Therefore it is critical in any assessment of sustained forces to consider the terrain on which the forces are to be exerted, and integrate this knowledge into any recommendations that are made.

Ending Forces

Unfortunately ending forces have received little attention in the literature. In the present study, an extensive understanding of the ending forces required to bring a pallet jack loaded with different loads to a stop was intended. Similar to the initial forces, the ending forces required of any task are only applied for a limited time period. Thus the results reported in Figure 13 represent peak ending forces in accordance with research by van der Beek **et al.** (1999).

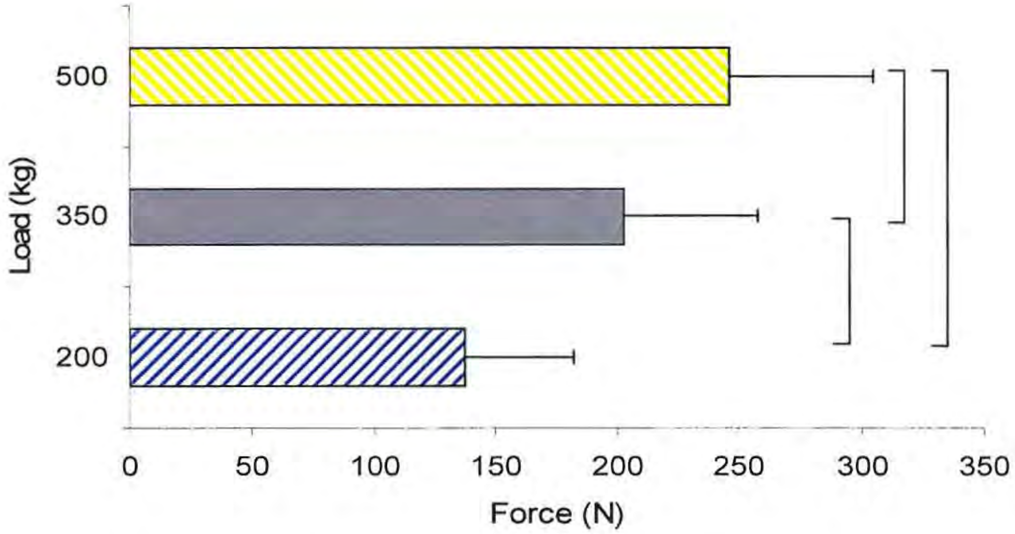

Figure 13: Mean peak ending forces (PE) exerted at each load, with SD shown. Vertical bars link loads with significant differences ($p<0.05$).

As with initial and sustained forces, all the ending forces were significantly different ($p<0.05$) at each load, highlighting the importance of load weight as a consideration in any pushing and pulling investigation. The forces shown in Figure 13 represent an investigation into the ending forces of a dynamic pushing task with controlled speed. It is interesting to note that as the load increases, so the amount of force required to stop the pallet jack, as a percentage of load decreases. The required force dropped from 7% of the load at 200kg, to 5% at 500kg. Van der Beek **et al.** (1999) also reported significant differences in the ending forces of their pushing tasks, which required ending forces between 170N and 265N for loads between 130kg and 400kg, and also demonstrating a decrease in the force required as a percentage of load, dropping from 13.3% at 130kg to 6.7% at 400kg. The reason for the higher magnitude possibly relates to the displacement speed at which their study was conducted, more than to the loads which were pushed. This indicates the importance of investigating impact of speed on responses to pushing and pulling tasks.

When a pallet jack or other MHD must be brought to a stop and sometimes positioned correctly, the forces can be significant and multidirectional. High force requirements in the ending phase, like the initial phase, increase fatigue and contribute to overexertion accidents such as muscle strains of the shoulders, arms and back (Eastman Kodak, 1986; Hoozemans **et al.**, 1998).

No literature exists regarding limitations or guidelines to MHD loads to minimise the forces required to bring an object to rest. It would be incorrect to apply the guidelines of pulling tasks to the ending phase of a pushing task, despite the force being a pulling force by definition. The differences in circumstances leading up to the exertion of the force are too different for a comparison to be valid.

Peak Initial vs. Peak Ending Forces

Pushing and pulling literature to date has tended to concentrate on the strength potentials of each form of task execution, and thus on the differences that arise between pushing and pulling (Schibye **et al.**, 2001; Laursen and Schibye, 2002; Hoozemans **et al.**, 2002; Haslam **et al.**, 2002; James and Todd, 2003; Hoozemans **et al.**, 2004). Limited research has attempted to investigate differences between initial, sustained and ending forces, and has focused on a very limited aspect of each task.

Initial forces have received most of the attention in the literature (Resnick and Chaffin, 1995; Schibye **et al.**, 1997; Al-Eisawi **et al.**, 1999; Haslam **et al.**, 2002; Ciriello, 2005), due to the fact that they are expected to be the highest, and therefore the biomechanical limiting factor in any pushing task. However, the ending forces occur within similar situational properties, with inertia playing a major role in determining the force required. A thorough understanding of the peak forces exerted in the initial and ending phases of a dynamic pushing task is thus imperative in fully understanding the biomechanical demands of the task. It would be expected that the extent of these peak forces are likely to contribute to the development and onset of musculoskeletal injuries (acute and chronic); the simultaneously applied static and dynamic forces are also equally likely to contribute to increases in energy expenditure and fatigue; and the postures and use of body mass in exerting these forces predisposes the operator to situations of instability, thus raising the possibility of slip, trip and fall accidents, and subsequent injury.

Figure 14 shows a comparison between the exerted forces in the initial and ending stages of the current dynamic pushing task, for each of the three loads tested. Both forces are likely to be the forces which contribute to both traumatic or long term injury onset and development.

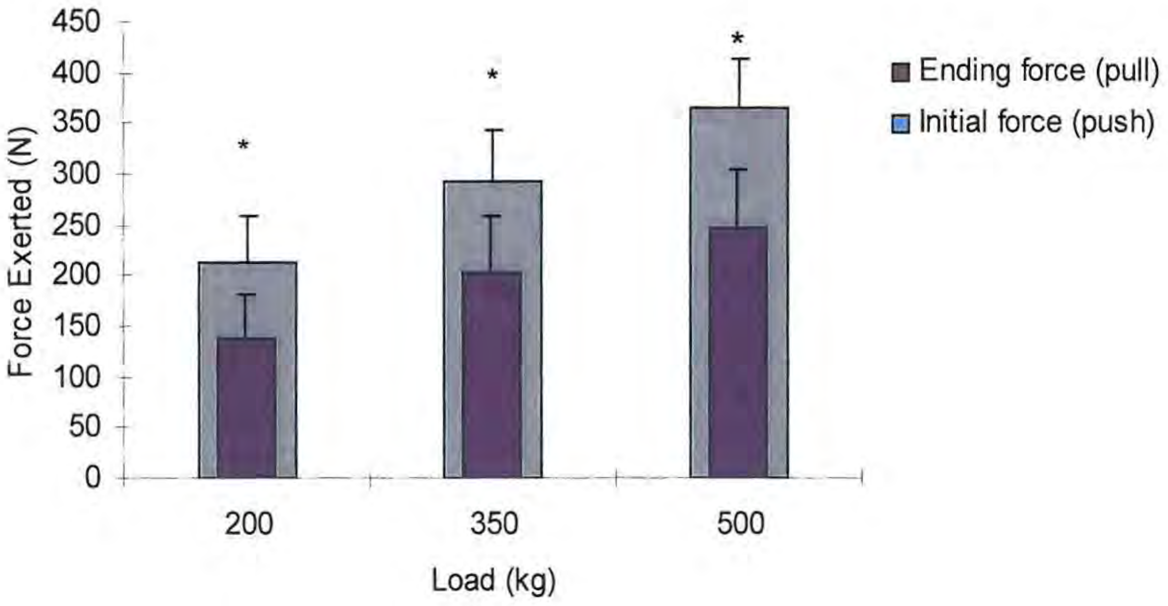

Figure 14: Mean peak initial (PI) and ending (PE) forces exerted at each load.

* denotes loads in which a significant difference ($p<0.05$) exists.

Results from the current research indicate that the peak ending (pull) forces are significantly lower than the peak initial (push) forces for each load. However, different methodologies and subject characteristics may alter the applicability of these findings. Industrial workplaces provide a variety of situations which require subjects to exert forces in different directions, assuming different body postures. This important finding indicates that given sufficient space or time in which to control the stopping movement, as well as appropriate worker education, ending forces can be reduced to pose a lower risk than the initial forces.

In the present experimental conditions, the ending forces required at each load represented 64.8%, 68.8% and 67.2% (mean 66.93%) of the initial forces for each load (200kg, 350kg and 500kg) respectively. Finding similar ratios for all loads suggests that it may be possible to predict the ending forces, based on the load and measurement of the initial forces, thus minimising lengthy investigations. However, basing guidelines or limitations to ending forces based on initial forces may be fundamentally flawed. The role of friction and stopping or starting distance are the factors most likely to contribute to the differences between initial and ending forces. Equally so, the muscle groups utilised and muscular contractions required to perform each action are different. Each pushing condition present in industry therefore needs to be investigated on its own merits.

Role of the Human Operator

While trying to exert sufficient force during pushing tasks, operators expose themselves to potentially unstable postures, and risk of injury due to STF accidents (Lee **et al.**, 1992). The high occurrence of occupational injuries due to overexertion during pushing is well recognised (Boocock **et al.**, 2006; Ciriello, 2005), and the majority of pushing related research has concentrated on the exerted forces at the hands (Hoozemans **et al.**, 1998; van der Beek **et al.**, 1999). The loads moved during pushing and pulling tasks in IDCs are substantially higher than those required to be moved manually in more advanced countries, therefore requiring increased force output (James and Todd, 2004). Under dynamic conditions, assessment of exerted forces becomes a complex investigation owing to the different stages of the task in which forces are exerted (initial, sustained and ending).

Table IX highlights the role of operator's body mass in contributing towards the exerted forces required in each of the three phases of a dynamic pushing task.

Table IX: Mean PI, AS and PE forces (N) exerted at each load with mean exerted force per kilogram body mass (SD in brackets).

		200kg	350kg	500kg
Initial Phase	Mean Force (N)	212.77	293.71	366.28
	Mean N.kg^{-1}	2.71 (±0.59)	3.76 (±0.84)	4.66 (±0.65)
Sustained Phase	Mean Force (N)	50	89.15	125.6
	Mean N.kg^{-1}	0.64 (±0.11)	1.14 (±0.19)	1.60 (±0.23)
Ending phase	Mean Force (N)	137.83	202.21	246.44
	Mean N.kg^{-1}	1.74 (±0.52)	2.58 (±0.75)	3.13 (±0.70)

As the load of the object increases, so too does the amount of force required per kilogram of body mass. As the forces exerted in the initial phase are the highest, so too is the demand per kilogram of body mass. The exerted forces are lower per kilogram in the ending phase and lowest in the sustained phase. The relationship between exerted push forces and musculoskeletal disorders has not been widely investigated, but it would seem plausible that any increase in force would increase the risk of a musculoskeletal disorder developing. Unfortunately, knowledge of the extent to which the body can cope with increasing biomechanical demands in dynamic pushing tasks is limited, and it is therefore difficult to evaluate whether or not these force requirements are beyond the capabilities of operators who perform pushing tasks on a regular basis. Hoozemans **et al.** (1998) raised this concern by acknowledging that attention has been paid to the mechanical loading of the lower back, but knowledge of upper extremity loading was insufficient.

Research by Lee **et al.** (1991) showed that body weight significantly affected the compressive forces in the lower back during pushing tasks, indicating that an increase in body weight would therefore not reduce the loading required by the musculature of the body. In addition Hoozemans **et al.** (1998 and 2004) researched the compressive and shear forces present in the lower back and shoulder joint during pushing and pulling tasks and concluded that "posture and movement largely determine the mechanical load compared to the exerted forces", therefore suggesting that mechanical loading is determined by factors other than the exerted forces. Furthermore, an increased body mass is accompanied by a decreased COF (Lee **et al.**, 1992), meaning that those who are strongest in relation to their weight are most liable to slip during the exertion of the force (Grieve, 1983). When pushing, the operator will seek to maximise the horizontal component of the force exertion, while still maintaining stability. Consequently, the vertical force, and in particular body weight, is an important factor for slipping as an increase in the downward force component is accompanied by a decrease in required COF (Boocock **et al.**, 2006). Fortunately initial forces typically last a short time, and drop to the sustained force levels once the acceleration and any mechanical interference at the start of the movement is overcome.

It can be seen from Table IX that the force requirements per kilogram of body mass in the sustained phase of the pushing tasks at each load were relatively small. However, they still exceeded the recommended guidelines in loads greater than 350kg, and therefore may be a limiting factor in any pushing task assessed biomechanically. Ciriello (2005) contended that during the sustained phase of a dynamic pushing task, the influence of body mass would be minimal, owing to the lack of change in posture. However, physiological considerations relating to the distance over which the forces are to be sustained would become the overriding ergonomic interest.

It becomes important to consider that the ratios shown in Table IX would increase if only the active skeletal muscle were considered. In addition, a percentage of that load is also being borne by the musculature in a static nature, which is well documented as contributing to increased cardiovascular responses and hastening the onset of fatigue (Konz, 1998). Nevertheless, the manner in which a risk factor leads to an injury/ disorder is usually through the accumulation of exposure to risk factors (Hoozemans **et al.**, 1998). Pushing heavy loads will stress soft tissue structures in the arms, shoulders, back and legs, but the exposure may be too low for traumatic injury, and thus the tissues recover. Repeated exposure to this stress may interfere with the normal recovery process and produce disproportionate responses and eventually a MSD-type injury.

The South African working population is frequently characterised by individuals (male and female) who are poorly nourished, and thus lack the muscular physique similar to the subjects used in the current study. For this reason, many of these forces may be excessive for them, and place their bodies under undue stress. The long term implications of such consistent exposure to musculoskeletal loading of this nature are documented extensively (Marras, 2000) and indicate that any consistent long term exposure will result in a diminished work capacity, and an increased risk of more severe chronic injuries.

Suitable MHD design minimises the forces required to be exerted by the operator by effectively reducing friction, and increasing the role of momentum in maintaining the required speed and direction. This has important implications for possible fatigue and long term musculoskeletal damage. The majority of studies determining the physiological responses to load movement have relied on relatively short term tasks, and have therefore not taken into consideration the energy cost over time and cumulative fatigue (Patton **et al.**, 1991). The statement above was made in relation to prolonged load carriage, but would still be applicable in pushing and pulling research, where no research has investigated the cumulative or long term effects of sustained load manipulation by pushing or pulling.

GAIT PATTERN RESPONSES

Also of interest in the current study were the gait pattern responses of individuals during the sustained phase of each load/frequency combination. Menz **et al**. (2003) argued that the maintenance of stability for the human postural control system is a difficult task for several reasons. Firstly because the centre of mass (COM) is located a considerable distance away from the support surface and secondly because the body is supported by one leg for a significant period of the gait cycle, with the COM outside of the base of support. The potential for loss of balance is therefore high, and is dramatically increased when an individual is required to simultaneously push or pull objects. Further, when movements are dynamic, such as during pushing and pulling tasks, postures and forces rapidly change during the course of the exertion, and maintaining an optimal posture becomes increasingly difficult (Resnick and Chaffin, 1995).

Table X: Stride length (m) and cadence (steps.min^{-1}) recorded during each experimental condition.

(Means with standard deviations in brackets, %= coefficient of variation)

		Stride length (m)	Cadence (steps.min^{-1})	Stride length (m)	Cadence (steps.min^{-1})	Stride length (m)	Cadence (steps.min^{-1})
Load	500kg	1.37* (0.09) 6.6%	111.9 (4.75) 4.2%	1.33 (0.08) 6.0%	105.2 (7) 6.7%	1.31 (0.08) 6.1%	105.0 (6.1) 5.8%
	350kg	1.36 (0.08) 5.9%	108.6 (6.9) 6.4%	1.32 (0.09) 6.8%	105.0 (6.4) 6.1%	1.33 (0.10) 7.5%	103.9 (6.7) 6.4%
	200kg	1.33 (0.10) 7.5%	109.9 (6.0) 5.5%	1.30* (0.09) 6.9%	109.0 (6.5) 6.0%	1.31 (0.08) 6.1%	106.8 (6.0) 5.6%
		1/20 sec		1/40 sec		1/60 sec	

Frequency

* denotes a **statistically significant difference** (p<0.05).
Shading identifies conditions with similar responses.

This introductory attempt to investigate gait patterns during pushing tasks will provide useful information to understand the mechanisms of slip, trip and fall accidents while using manual handling devices.

Stride Length

Changes in stride length, measured from heel strike on the right foot to heel strike again, can be indicative of the impact on natural walking patterns of the task demands. It would be expected that as the task demands increase, particularly in a dynamic task such as pushing and pulling, so an individual's stride length would adjust in order to accommodate these demands.

Under the current testing conditions it was found that load had no effect on an individual's stride length ($p<0.05$). This finding emphasises the need for future research into gait responses at different velocities during pushing, as speed was controlled in this study. No clear pattern arose according to load, further indicating the minimal role load played in influencing these responses. Despite this, it is interesting to note the range of stride lengths, with the shortest stride length of 1.11m recorded during condition 5 (350kg every 40 seconds), while the largest stride length reached of 1.55m was recorded during condition 8 (350kg every 60 seconds). This range highlights the variability within even controlled samples, and provides valuable insight into the range of human responses to identical tasks.

Interestingly, while load had no effect on stride length responses, frequency did significantly affect the responses recorded (see ANOVA table in Appendix C). It would have been expected that because walking speed was controlled throughout the study, that frequency would play a small role in altering the gait pattern responses. However, the stride lengths recorded at the highest frequency were significantly different to those recorded at the intermediate and the slowest frequency.

These findings indicate that the subjects chose to adjust their stride length due to the demands placed on them by the frequency of the task as opposed to the load of the object being moved. Although statistically significant results arose between the highest frequency and the intermediate and slowest frequency, the greatest difference was less than 3% between stride lengths. This important finding shows that despite a statistically significant difference, the practical relevance must be considered foremost. In practical application, such a small difference in stride length would have no major implications for an individual's gait pattern, or subsequent energy expenditure.

Future research would be advised to consider the role of frequency by investigating stride length responses through a range of walking speeds and differing frequencies, in order to clarify the importance and role of frequency on gait pattern responses, and the possible link to energy expenditure.

The interaction effects of load and frequency play a large role in determining gait pattern responses, and could be related to changes in energy expenditure, or the onset of fatigue in the long term. Dynamic pushing therefore did not appear to change responses as load and frequency changed. However, gait pattern responses need to be compared to natural gait patterns, which may be substantially different. This finding may further suggest that it is in fact the posture adopted which is of greater importance to stability and slip, trip and fall accidents, than the gait responses.

The second measure of gait assessed in the current study was individuals' cadence responses and the impact of load and frequency individually and in combination. The primary goal in any human movement is energy efficiency in progression, and higher cadence is a primary contributor to higher energy expenditure, and vice versa.

Cadence

Cadence, measured as the number of steps taken per minute, is an important indicator of gait pattern responses, as it is relatively easy to identify any changes due to the task demands. It has been shown that load and frequency had minimal effects on an individual's stride length.

Frequency had an impact on cadence, with statistically significant differences ($p<0.05$) arising between the highest frequency and each of the other two frequencies. Once again the statistical significance is overshadowed by the practical relevance. Despite a statistical difference existing, the largest practical difference between two frequencies is less than five steps per minute, which is minimal. Alternatively, it was expected that load would influence cadence, but as seen in Table X, the only significant difference arose between the 200kg and 350kg load. This was unexpected, as it was anticipated that the difference would arise between the lightest and the heaviest loads. This finding indicates that during the sustained phase of the dynamic pushing tasks, because subjects are only required to maintain momentum, and not overcome or reverse inertia, gait pattern responses are similar regardless of load weight or frequency of task.

As with stride length, it would be interesting for future researchers to investigate the gait responses in relation to the individuals' natural gait pattern. The gait analysis in this study was limited to the sustained phase of the task, and hence responses during the initial or ending phases are not reflected. It would be expected that responses during these stages would provide critical information, particularly regarding stability and the possibility of slip, trip and fall accidents occurring.

PHYSIOLOGICAL RESPONSES

Musculoskeletal injuries continue to plague industry, and the relationship between task and cost is always present (Ciriello **et al.**, 1999b). Techniques for analysing manual handling tasks take a variety of forms, including physiological assessments (Dempsey, 1998). By their nature, manual handling tasks pose physical stresses on the operator, which are manifested as musculoskeletal and cardiovascular strains.

Once the strain imposed exceeds the capabilities of the worker, potential exists for injury, discomfort or fatigue (Dempsey, 1998).

Research into physiological responses to MMH tasks is concerned with the physiological stresses placed on the body. During repetitive tasks, large muscle groups perform repeated dynamic contractions, testing the worker's endurance capacity, which is limited by the capacity of oxygen transportation and utilisation systems, and not their muscular strength (Bridger, 2003). The goal of physiological research is to develop limits based on metabolic and cardiovascular criteria, and then determine task specific capacities based on these chosen criteria (Ayoub, 1984).

Central to the drive for productivity improvement is the challenge of finding an acceptable work rate and load for a given job. Workloads are acceptable provided the stress does not interfere with worker's functions and their capacity to operate the system safely and efficiently (Jung and Jung, 2001). Thus, the goal of the ergonomist is to determine the maximum levels of a workload that do not violate a physiological 'steady-state'.

Heart Rate responses

Metabolic energy expenditure and heart rate are the physiological measurements that are used most often to determine the maximum task intensity that can be continuously withstood without accumulating an excessive amount of physical fatigue (Shoaf **et al.**, 1997). As heart rate is more easily measured than oxygen consumption, heart rate is regularly used as an indirect measure of energy expenditure (Bridger, 2003), or an index of physiological workload. Research into the physiological responses associated with lifting tasks has demonstrated that load and frequency can influence cardiovascular responses either individually, or in combination (Khalaft **et al.**, 1999). The current research aimed to identify whether this interaction existed for dynamic pushing tasks. Table XI identifies the heart rate responses to all nine experimental conditions.

Table XI: Working heart rate responses (bt.min^{-1}) recorded during each experimental condition.

(Means with standard deviations in brackets, %= coefficient of variation)

Load				
	500kg	▨ ^{3} 132 (15.1) 11.4%	^{6} 101* (13.4) 13.3%	^{9} 93*▲† (12.3) 13.2%
	350kg	▨ ^{2} 114 (14.4) 12.6%	^{5} 95*¶# (11.1) 11.7%	^{8} 88^▲¶ (10.8) 12.3%
	200kg	^{1} 101* (14.8) 14.7%	^{4} 90^#† (9.5) 10.6%	^{7} 81^ (10.1) 12.5%
		1/20 sec	1/40 sec	1/60 sec

Frequency

*, ^, ▲, ¶, #, † denotes **statistically similar responses ($p<0.05$).**
Shading denotes conditions exceeding current guidelines.

Condition 3, which required the subjects to push a 500kg load every 20 seconds, created the highest cardiovascular demand, with a mean heart rate of 132bt.min^{-1} (±15.1), while condition 7 which combined the lightest load with the lowest frequency had the lowest heart rate response of 81bt.min^{-1} (±10.1). For each load, the highest heart rate responses were recorded at the highest frequency condition, with the lowest recorded heart rate at the slowest frequency. Significant differences ($p<0.05$) were established between the highest and the other two frequencies for all loads, with no significant difference occurring between the intermediate and slowest frequency. The time taken to complete one push was the same regardless of the frequency of the condition; however, slower frequencies allowed greater recovery time (up to 40 seconds) between each push exertion. This finding indicates that there were much greater intra-subject variations at slower frequencies, due to the 20 to 40 seconds of inactivity, which was not evident at the faster frequency. Since the highest frequency tasks were significantly different from all other frequencies, it is apparent that there was insufficient time between exertions for the subject's heart rate to decrease.

Increasing the load played an increasingly important role as pushing frequency increased, with the mean heart rate response differences between the intermediate and high frequencies being 12.1%, 20.3% and 30.5% for the 200kg, 350kg and 500kg loads respectively. This finding suggests that an individual's heart rate responses are not likely to differ whether they are performing dynamic pushing tasks once every 40 seconds or once per minute. Importantly it highlights the fact that as the load increases, so the effect of frequency becomes more pronounced, particularly at the higher frequencies.

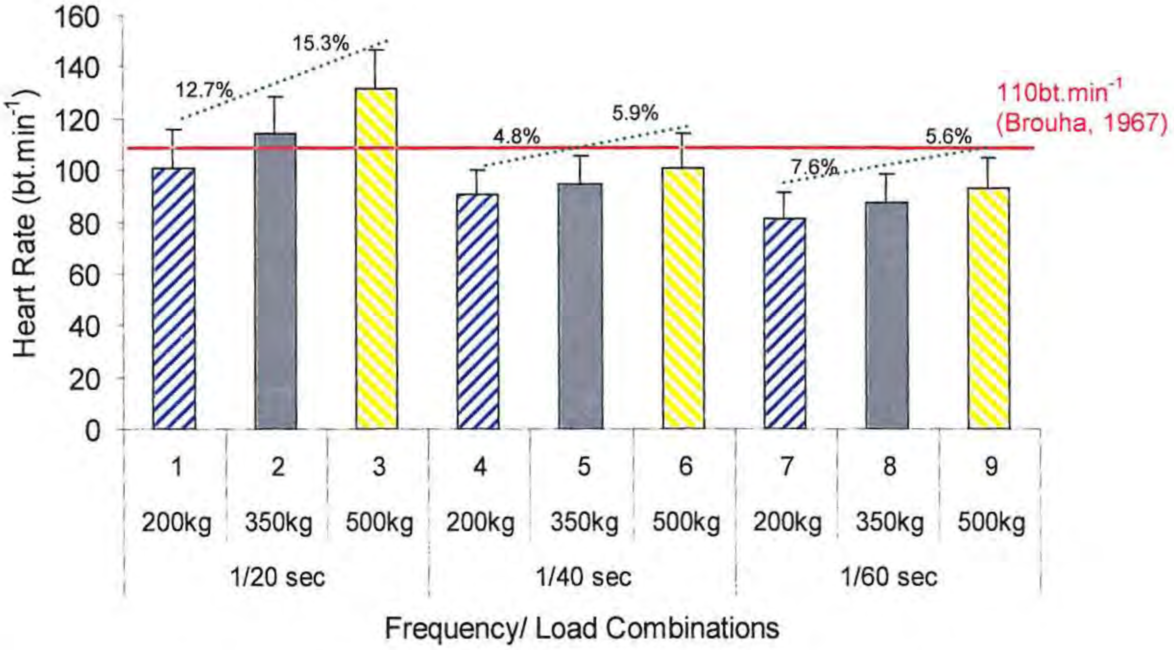

Figure 15: Heart rate (bt.min^{-1}) responses as a function of load at each frequency, in relation to the suggested physiological limit.

(% shows increase between conditions).

An increase in working heart rate is apparent as the load of the object being pushed increased. Significant differences ($p<0.05$) were found between all three loads at the highest frequency, and between the 200kg and 500kg loads for the intermediate and slowest frequencies. It is therefore evident that the impact of load was much greater at higher frequencies, and that at frequencies slower than once every 40 seconds, there is no difference between loads of 200kg and 350kg. Although at low frequencies increasing the load resulted in an increase in heart rate, these increases were more marked at high frequencies (see Figure 15).

The increase in working heart rate between loads of 350kg and 500kg (5.9% and 15.3%) exceeded the increase in heart rate from the 200kg to 350kg loads (4.8% and 12.7%) at both the intermediate and highest frequencies respectively. However, at the slowest frequency, the opposite is found, with the difference between 200kg and 350kg (7.6% increase) exceeding the change between 350kg and 500kg of 5.6%.

It becomes apparent that although responses can be broken down to the contributing components, the greatest knowledge will be gained by understanding the combined effect of load and frequency. Table XI identifies the integrated responses on subjects' heart rate responses. Significant differences ($p<0.05$) were established for a number of conditions, in particular between conditions 2 and 3 and all the other conditions, since these conditions combined the two heavier loads with the fastest frequency. The combination of high frequency and moderate or heavy load resulted in statistically higher heart rate responses, with both conditions 2 and 3 above the 110bt.min^{-1} limit recommended by Brouha (1967), Åstrand and Rodahl (1986) and McArdle **et al**. (2001), indicating that these combinations are likely to lead to fatigue. It is evident in Table XI that all other responses can be classified as moderate, with condition 7 considered light, only having an average heart rate of 81bt.min^{-1}. Some conditions recorded statistically similar responses ($p<0.05$) highlighting the importance of examining the integrated impact of load/frequency combinations on physiological responses.

Van der Beek **et al.** (2000) investigated heart rate responses within dynamic pushing tasks, under conditions similar to those tested in the current study. Mean heart rate responses achieved are very similar to those recorded in the current investigation, ranging between 101 and 131bt.min^{-1}. The heavier cages used by van der Beek **et al.** (2000) at an intermediate/high frequency are illustrative of the high physiological demands that could be experienced by workers within industry. Heart rate responses from the current study were achieved under 'optimal' conditions (design and environmental). This emphasises the need to apply these findings from a controlled laboratory environment back into the industrial setting, where conditions may be sub-optimal thereby increasing the task demands. The impact of frequency on physiological demands is dependent on the load being moved. Therefore these two critical task characteristics need to be investigated together, rather than in isolation. However, it must be cautioned that heart rate should not be used as a sole measure of physiological cost associated with any task, as it varies substantially between individuals, and is highly influenced by many extraneous factors, such as the physical differences and environmental differences discussed in Chapter 2.

Oxygen Consumption ($\dot{V}O_2$) and Energy Expenditure

The classical method of determining energy expenditure while performing work tasks involves the measurement of oxygen consumption. The commencement of any physical exertion requires the recruitment of muscle fibres and thus an increased oxygen consumption demand to provide the required energy (McArdle **et al**., 2001). In the current research, oxygen consumption was measured throughout the six-minute protocol of each condition. However, an analysis using T-tests between minute 4 and minute 6 indicated that no significant difference existed for any condition, and thus physiological 'steady state' had been reached. Only results for the final minute are therefore shown and reported on. Results were analysed to determine the existence of frequency effects, load effects and combined load/frequency effects.

Table XII: Mean relative ($mlO_2.kg^{-1}.min^{-1}$) and absolute oxygen uptake ($L.min^{-1}$) recorded during each experimental condition.

(Means with standard deviations in brackets, %= coefficient of variation)

Load	$mlO_2.kg^{-1}.min^{-1}$	$L.min^{-1}$	$mlO_2.kg^{-1}.min^{-1}$	$L.min^{-1}$	$mlO_2.kg^{-1}.min^{-1}$	$L.min^{-1}$
500kg	3 26.06 (3.78) 14.5%	2.06 Very heavy	6 17.02* (2.63) 15.5%	1.35 moderate	9 13.64▲ (2.33) 17.1%	1.08 moderate
350kg	2 21.68 (3.61) 16.7%	1.71 Heavy	5 13.85▲ (2.09) 15.1%	1.10 moderate	8 11.21^ (2.02) 18.0%	0.89 light
200kg	1 16.71* (2.77) 16.6%	1.32 moderate	4 11.15^ (1.77) 15.9%	0.88 light	7 9.67^ (1.37) 14.2%	0.76 light
	1/20 sec		1/40 sec		1/60 sec	

Frequency

*, ^, ▲ denotes **statistically similar** responses ($p<0.05$).
Shading denotes conditions which exceed recommended guidelines.

The highest mean oxygen consumption value of $26.06mlO_2.kg^{-1}.min^{-1}$ was recorded for the task which combined the heaviest load at the highest frequency. The lowest mean oxygen consumption ($9.67mlO_2.kg^{-1}.min^{-1}$) was recorded during condition 7, which combined the lowest load and slowest frequency. These results are similar to those recorded for heart rate responses discussed earlier. As anticipated, the highest oxygen consumption always occurred at the highest frequency, with the lowest oxygen consumption coinciding with the lowest frequency. Significant differences ($p<0.05$) were established between all three frequencies tested in the current experimentation at all three loads.

The effect of frequency on oxygen consumption responses showed a similar pattern for all loads, with the difference between the fastest frequency and the intermediate frequency being greater than the difference between the intermediate and slowest frequency (see Table XII). $\dot{V}O_2$ at 200kg showed a 49.8% and 72.8% increase from the lowest and intermediate to the highest frequency respectively. Noticeable differences occurred while pushing the 350kg load, where the highest frequency elicited a mean $\dot{V}O_2$ value of 21.68mlO$_2$.kg^{-1}.min^{-1}, which was 93.3% higher than the lowest frequency (11.21mlO$_2$.kg^{-1}.min^{-1}). Similarly, the responses recorded while pushing the 500kg load once every minute were 91% (13.64mlO$_2$.kg^{-1}.min^{-1}) lower than at the highest frequency.

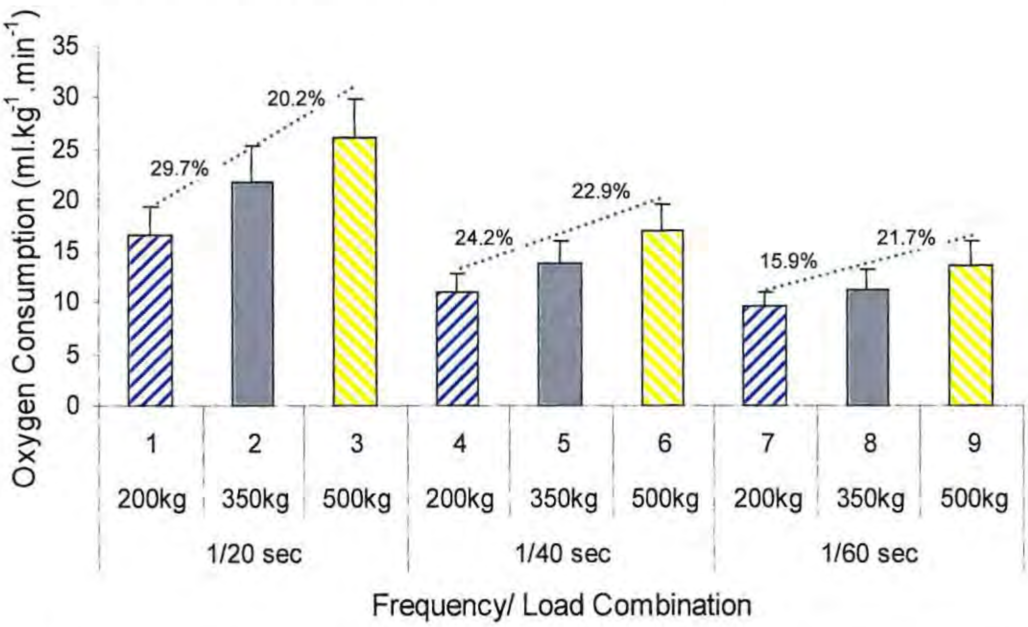

Figure 16: Oxygen consumption (mlO$_2$.kg^{-1}.min^{-1}) responses as a function of load and frequency.

(% shows increase between conditions).

Figure 16 shows that as the load increased there was a concomitant increase in the mean oxygen consumption values, at each frequency. Significant differences ($p<0.05$) arose between each of the three loads at the two higher frequencies, but not at the slowest frequency, where conditions 7 (200kg) and 8 (350kg) were similar to each other. The greatest increase in oxygen consumption as a result of load occurred with 500kg at the more rapid frequencies (1/20 and 1/40sec), which was 20.2% and 29.7% higher than the mean $\dot{V}O_2$ value at 350kg (21.69mlO$_2$.kg^{-1}.min^{-1}) and 200kg (16.71mlO$_2$.kg^{-1}.min^{-1}). This upward trend in oxygen consumption values between

200kg and 500kg loads is evident for each frequency, although the 'slope' is less steep at the slower frequencies.

Interestingly, at the intermediate and slower frequencies, although the percentage increase in oxygen consumption between the 200kg and 350kg loads is smaller than the same change at the highest frequency, the opposite is evident for the increase in load from 350kg to 500kg. Increasing the load from 350kg to 500kg at the intermediate and slower frequency elicited a higher percentage increase in oxygen consumption, than the same increase at a quicker frequency. This finding shows that at higher frequencies both load and frequency are important factors driving up oxygen consumption and hence physiological cost, whereas, at the slower frequencies, it is the load which becomes the driving factor.

When investigating load/frequency combination effects it is evident that there were more significant differences ($p<0.05$) for $\dot{V}O_2$ than for heart rate. Conditions 2 and 3, which combined the two heavier loads (350kg and 500kg) at the highest frequency were significantly different to all others. Conditions 4 and 8 and 5 and 9 all generated statistically similar $\dot{V}O_2$ responses, ranging between $11.15mlO_2.kg^{-1}.min^{-1}$ and $13.85mlO_2.kg^{-1}.min^{-1}$. This finding confirms the integrated effect of load and frequency. Therefore, making recommendations based on either load or frequency alone without due consideration of the integrated effect is likely to increase risk of incompatibility between task demands and the operator.

Conditions 4, 7 and 8 would be considered 'light' according to the guidelines of McArdle **et al**. (2001). Conditions 2 and 3 would be considered 'heavy' and 'very heavy' respectively, making them physiologically unfeasible, regardless of other factors, and are thus not recommended for repetitive work over prolonged periods. All other conditions would be classified as moderate and thus would need to be considered in terms of the biomechanical and psychophysical factors to determine their suitability for industry.

Van der Beek and associates' (2000) results provide a valuable comparison to the current study. Condition 5 required a mean $\dot{V}O_2$ of $1.1L.min^{-1}$, while van der Beek **et al.** (2000) found that pushing a lighter load (250kg) more frequently led to a lower oxygen uptake of $0.97L.min^{-1}$. Interestingly, the same authors also found that pushing a heavier load (400kg) required $1.08L.min^{-1}$ oxygen consumption, thus matching condition 5. The oxygen consumption values in the current study when pushing 500kg every 40 seconds reached a higher value of $1.35L.min^{-1}$, as opposed to the $1.30L.min^{-1}$ found by van der Beek **et al.** (2000) when pushing 550kg more frequently. Although the responses are not substantially different, the findings of the present research emphasise the fact that any task needs to be evaluated individually, and assessed on its merits, before a decision can be taken as to the likelihood of problems associated with the physiological impact of the task.

The importance of frequency (and hence stop/start nature) is highlighted when responses from the present study are compared to results from continuous pushing studies (Williams **et al.**, 1966; Wyndham and Heyns, 1967). Williams **et al.** (1966) found that continuous pushing of loads as high as 909kg required a $\dot{V}O_2$ of $1.4L.min^{-1}$, similar to the responses recorded while pushing 200kg every 20 seconds in the current study. Importantly, Wyndham and Heyns (1967) suggest that speed is the largest contributing factor to increased oxygen consumption values, until the load weight increases above 340kg. After 340kg, load increases in importance as a contributing factor. Similar results were attained in the present study, with load becoming increasingly influential above 350kg. It is, however, crucial to note that the impact of frequency and load will vary as walking speed varies, and this is an area which requires further investigation.

According to the American College of Sports Medicine (1986) healthy, sedentary individuals have $\dot{V}O_{2max}$ values of between 40 and 45 $mlO_2.kg^{-1}.min^{-1}$, while McArdle **et al.** (2001) report that 50% of untrained male college students should reach a maximal oxygen uptake of $45.8mlO_2.kg^{-1}.min^{-1}$. Authors such as Legg and

Pateman (1985) and Ayoub (1992) have recommended that workers should not perform tasks which are likely to require them to work at a $\dot{V}O_{2max}$ of 33% or more of predicted maximum, while Kemper **et al.** (1990) suggested an endurance limit of 30%$\dot{V}O_{2max}$.

Table XIII: Relative mean oxygen uptake ($mlO_2.kg^{-1}.min^{-1}$) measurements with percentage of predicted $\dot{V}O_{2\,max}$ indicated.

	500kg	^{3} 26.06 56.9%	^{6} 17.02 37.2%	^{9} 13.64 29.8%
Load	350kg	^{2} 21.68 47.3%	^{5} 13.85 30.2%	^{8} 11.21 24.5%
	200kg	^{1} 16.71 36.5%	^{4} 11.15 24.3%	^{7} 9.67 21.1%
		1/20 sec	1/40 sec	1/60 sec

Frequency

$\dot{V}O_{2max}$ calculated indirectly as (measured $\dot{V}O_2$/45.8)*100.
Shading denotes conditions exceeding recommended guidelines.

Pushing the 500kg load at all but the slowest frequency required an oxygen consumption at 30% or more of predicted maximum, while at the highest frequency, each load also required excessive energy expenditure. This finding reiterates the importance of investigating all contributing factors in a dynamic pushing task, as the combined responses provide valuable insight into the full complexity and demands of the task. These findings would further suggest that both loads of 500kg and frequencies of 1/20 seconds are likely to lead to fatigue and therefore lower productivity over time.

Investigating the cost of manual materials handling (MMH) tasks is of particular interest to ergonomists in developing countries, due to the abundance of manual labour. Understanding energy expenditure and the physiological cost of pushing tasks in industry is of paramount importance, as the prevalence of these tasks is on the increase. In South Africa, most of the manual labour force is comprised of Black and Coloured males who are involved in low paying occupations as a consequence of South Africa's past. Due to job scarcity workers are prepared to work under appalling conditions where tasks will often exceed any guidelines or limitations that are utilised in developed nations (Scott and Christie, 2004). Knowledge of the energy expended whilst performing dynamic pushing tasks was thus of critical importance to this study.

Oxygen consumption results were used to calculate mean energy expenditure values for each of the nine conditions tested in the current study, the results of which are shown in Table XIV.

Table XIV: Mean energy expenditure responses (kcal.min^{-1}) recorded during each experimental condition.

(Means with standard deviations in brackets, %= coefficient of variation)

Load		1/20 sec	1/40 sec	1/60 sec
	500kg	^{3} 9.85 (1.59) 16.1%	^{6} 6.39* (0.70) 11%	^{9} 5.13▲ (0.69) 13.5%
	350kg	^{2} 8.14 (1.01) 12.4%	^{5} 5.21▲ (0.63) 12.1%	^{8} 4.22^ (0.69) 16.4%
	200kg	^{1} 6.29* (0.88) 14%	^{4} 4.20^ (0.55) 13.1%	^{7} 3.64^ (0.46) 12.6%

Frequency

*, ^, ▲ denotes **statistically similar** responses ($p<0.05$).
Shading denotes conditions exceeding recommended guidelines.

Significant differences ($p<0.05$) were established between all frequencies at all three loads, highlighting the important impact of frequency on energy expenditure of pushing activities. As frequency increased, so a concomitant increase in energy expenditure occurred at each load. This finding supports prior research into the impact of frequency in lifting tasks, where higher frequencies would elicit higher energy expenditure values. The change in energy expenditure between the highest frequency and the intermediate frequency showed the greatest percentage change, with an average increase of 53.3%, compared to a change from the intermediate to slowest frequency of 21.1%.

At the lightest load of 200kg, the highest frequency therefore required a 72.8% increase in energy expenditure, as opposed to the slowest frequency. A similar pattern of responses were recorded at the intermediate and heavy loads, whereby overall energy expenditure increased by approximately 92% as the frequency increased from the slowest to the fastest.

It is evident then that decreases in frequency are accompanied by decreases in energy expenditure. Load, however, also plays a critical role in determining the energy required to effectively perform the task. Figure 17 demonstrates the role load had in influencing the energy expenditure responses.

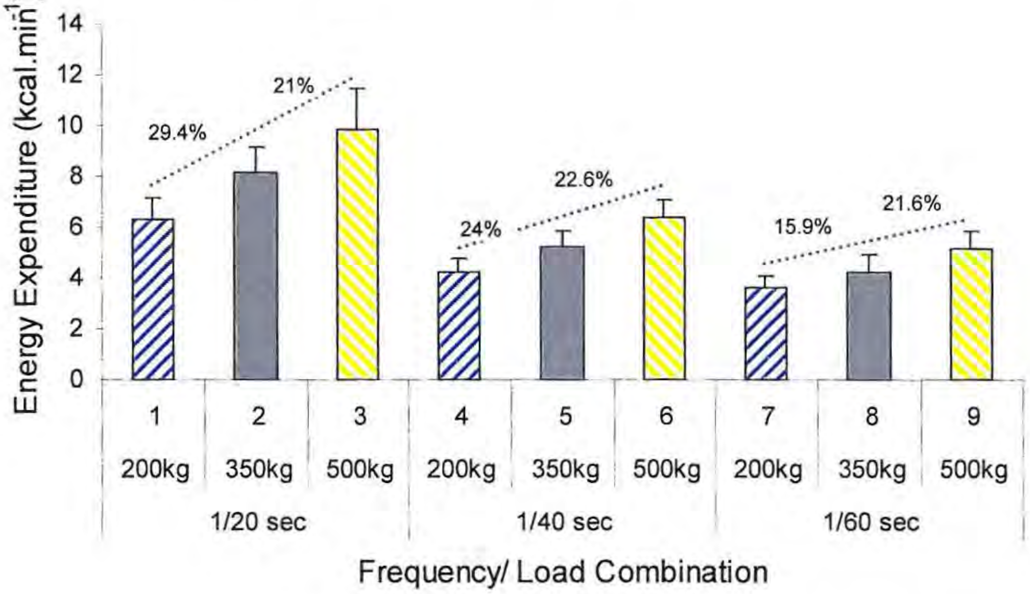

Figure 17: Energy expenditure (kcal.min^{-1}) responses as a function of load at each frequency.

(% denotes increase between conditions)

As load increased, so too did the required energy expenditure. Significant differences ($p<0.05$) as a result of load arose between all loads at the quickest and intermediate frequencies. However, at the slowest frequency, energy expenditure between the 200kg and 350kg loads was not significantly different, although the 500kg load was significantly greater than both.

As was expected, pushing the 500kg load required significantly greater energy expenditure than each of the other loads. The effect of load can be seen by the slope between each load at each frequency. The impact of load on energy expenditure was also found to be dependent on the frequency. This can be illustrated by the percent increases from 200kg to 500kg. At a frequency of 1/20 seconds, there was a 56.6% increase in energy expended for a 150% increase in load, which was only 52.1% and 40.9% at the intermediate and slow frequency respectively. These findings suggest that load plays an increasingly important role as the frequency of pushing increases, with the impact of load being more pronounced at loads in excess of 350kg.

The combination of the highest frequency and heaviest load required the highest energy expenditure, of 9.85kcal.min^{-1}, while the lightest load and slowest frequency condition required the lowest energy expenditure of 3.64kcal.min^{-1}. The findings also indicate that even at a frequency of 1/60 seconds, loads above 350kg play a critical role in determining energy expenditure. At the lightest load of 200kg, no significant difference arose between conditions 4 and 7 (3.64kcal.min^{-1}), indicating that due to the light load, any frequency slower than once every 40 seconds would require a similar energy output, and that it is likely to be attributed to load driving the energy requirement.

Haisman **et al.** (1972) examined the energy cost of pushing loaded handcarts and found a mean energy expenditure of 6.91 (±0.6) kcal.min^{-1}, for loads as little as 50kg, and speeds as slow as 1.56m.s^{-1} (5.6km.h^{-1}). This finding was unexpected, considering that in the present research, this value was only exceeded by the two heaviest loads at the highest frequency. Haisman **et al.** (1972) carried out testing on a treadmill and an asphalt surface, which may have substantially increased the coefficient of friction, which would consequently drive up the resistance to movement and thus the energy required to perform the task. Once again though, a comparison between continuous and intermittent tasks is difficult since subjects in Haisman and associates' investigation pushed for 30 minutes, while the current research investigated the more common intermittent pushing tasks, as evidenced in industry.

Despite the importance of knowing the energy expenditure associated with any particular manual materials handling task, no guidelines or criteria currently exist for dynamic pushing tasks. The energy expended by the subjects in the current study was therefore compared to the general guidelines provided in McArdle **et al.** (2001).

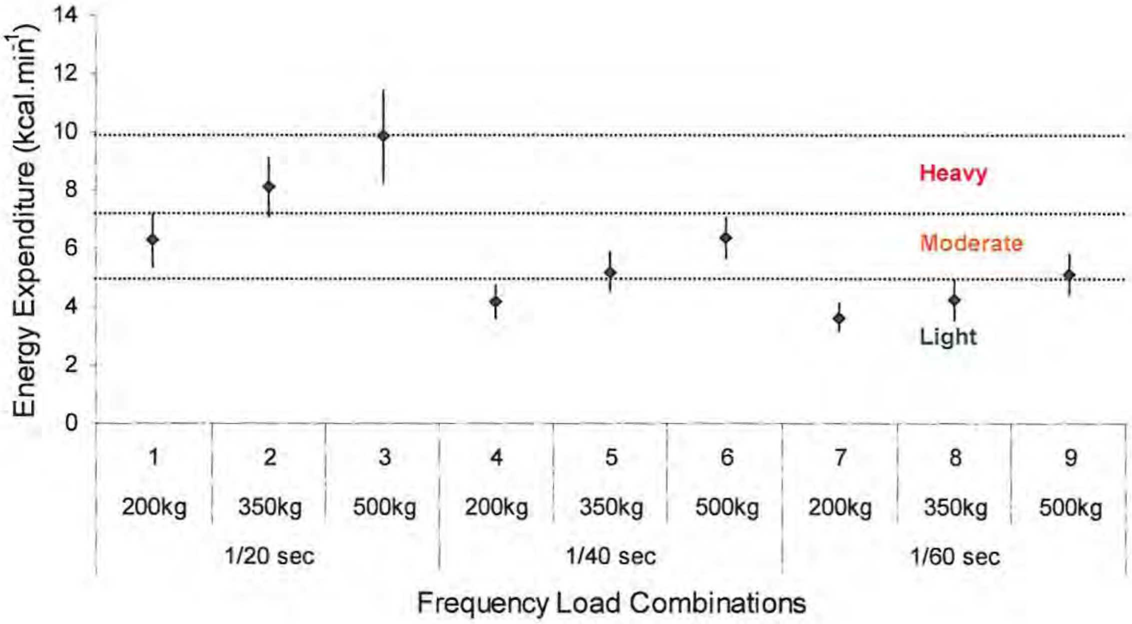

Figure 18: Energy expenditure (kcal.min^{-1}) responses of each experimental condition, with demarcations showing classification of exercise intensity (from McArdle et al., 2001).

From Figure 18 it is evident that conditions 1 and 2 (350kg and 500kg, 1/20sec) resulted in an energy cost which would be considered to be unduly taxing, and thus would not be recommended from a physiological perspective. Individuals within industry would be unable to maintain this intensity for any extended period without fatigue setting in.

Only conditions 4, 7 and 8 fell into the 'light' classification, and could possibly be considered as sustainable tasks, provided that other contributing factors did not deteriorate, which in turn would increase energy cost. It is interesting to note however, that even at the slowest frequency, a load of 500kg required energy expenditure which could be considered as 'moderate'. This indicates that the loads pushed in industry need to be carefully controlled, and even at slow, intermittent frequencies, and under optimal conditions, could require high levels of energy expenditure. This finding suggests that loads greater than 500kg should only be moved on an irregular basis or by a semi-automated system, as the load is enough to require substantial energy contribution for the individual operators.

Conditions 1, 5, 6 and 9 are classified as moderate according to McArdle **et al.** (2001). These conditions are thus acceptable from a physiological perspective, provided that other factors, such as pallet jack maintenance, handle height and floor friction remain optimal. However, cognisance of other factors from a biomechanical and perceptual basis needs to be taken into account in order to determine the long term suitability of such tasks in industry, and risk of developing musculoskeletal problems. In South Africa, this investigation needs to be extended further to consider the energy intake of operators, as the poor economic state of the individuals involved in MMH regularly leads to a dietary imbalance with energy expenditure dramatically exceeding intake. This imbalance leads to long term/chronic fatigue and the increased possibility of additional musculoskeletal strain.

***In situ* applicability**

The workload of a given task cannot always be inferred directly from measures of output. Physiological methods reflect the effort that the worker puts into the work system rather than the output of the system itself. Physiological measures are a representation of the effect of the work on the human operator, as opposed to the worker on the work task (Bridger, 2003). Therefore, setting energy expenditure limits for MMH tasks is difficult and appropriate measures, specific to the task need to be utilised.

An investigation into the relationship between heart rate and oxygen consumption responses for a dynamic manual task such as pushing provided insight into the relationship between these physiological variables. In Figure 19 this relationship is plotted in order to determine whether a simple measure such as working heart rate could be used to predict the oxygen consumption associated with a dynamic pushing task similar to that of the current study.

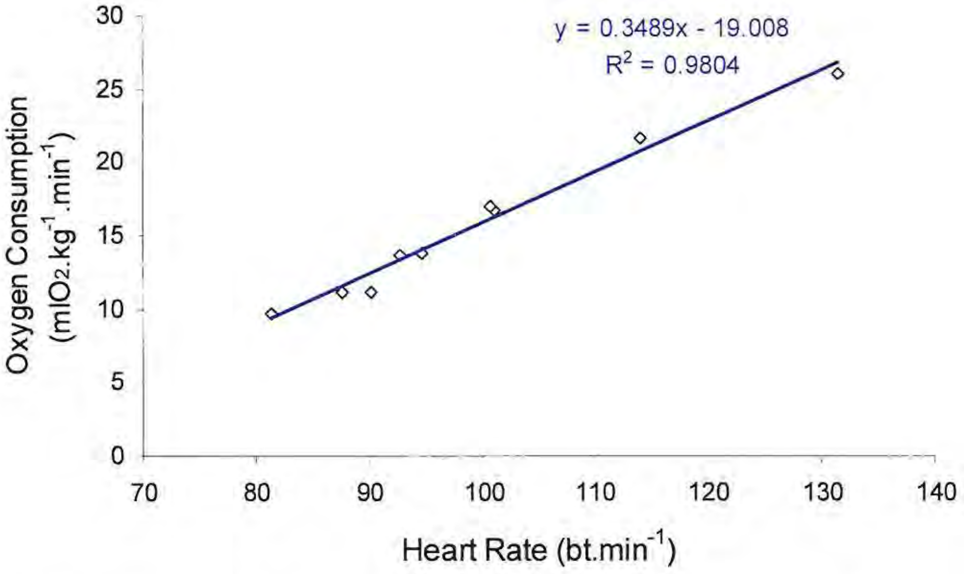

Figure 19: Relationship between heart rate and oxygen consumption.

In the relationship shown in Figure 19, both the load and frequency effect can be clearly seen. This regression equation derived determines the mathematical relationship between heart rate and oxygen consumption. As was expected, the relationship is positively linear, showing that higher heart rate responses are associated with increased oxygen consumption. The regression depicted in Figure 19 represents the group regressions, and as such individuals may differ from the trend depicted. However, once the heart rate/$\dot{V}O_2$ relationship is determined for each individual, it would be possible to accurately predict future oxygen consumption. A comparison between actual and predicted results determined that for each load/frequency combination, the predictive capacity was very high. Table XV summarises the actual versus predicted results, and highlights the difference that arose between them.

Table XV: Actual vs. predicted oxygen consumption, with percentage difference.

		Actual		Predicted	
Load (kg)	**Frequency**	**HR**	**$\dot{V}O_2$**	**$\dot{V}O_2$**	**% Difference**
200	1/20sec	101	16.71	16.29	2.5
200	1/40sec	90	11.15	12.49	10.7
200	1/60sec	81	9.67	9.4	2.9
350	1/20sec	114	21.68	20.78	4.3
350	1/40sec	95	13.85	14.06	1.5
350	1/60sec	88	11.21	11.58	3.2
500	1/20sec	132	26.06	26.88	3.1
500	1/40sec	101	17.02	16.14	5.5
500	1/60sec	93	13.64	13.39	1.9

Heart rate (HR) in bt. min^{-1}; Oxygen consumption ($\dot{V}O_2$) in $mlO_2.kg^{-1}.min^{-1}$

(**Blue** identifies an under-prediction, while **red** identifies an over-prediction).

Such findings have important implications for industry whereby the physiological cost of a pushing task could be accurately determined through a simple measure such as a heart rate response, provided that due consideration is given to the frequency and load of the task. Such minimal differences between actual and predicted results are unusual in ergonomics research. In lifting research, the best predictive results has over-predicted by as much as 20% (Sothmann **et al.**, 1991). Over-predictions of a task's energy cost, however, may provide a valuable "protection" to the worker.

Of easier reference for practitioners in industry would be the existence of a relationship between load and heart rate or oxygen consumption. This would allow individuals to gauge the extent to which they are going to be taxed physiologically, simply through the load/heart rate or load/$\dot{V}O_2$ relationship. Once again though, consideration must be given to the effect of frequency, as higher frequencies exert a substantial influence on the physiological responses. Figure 20 demonstrates the load/heart rate and load/$\dot{V}O_2$ relationship derived for the current study.

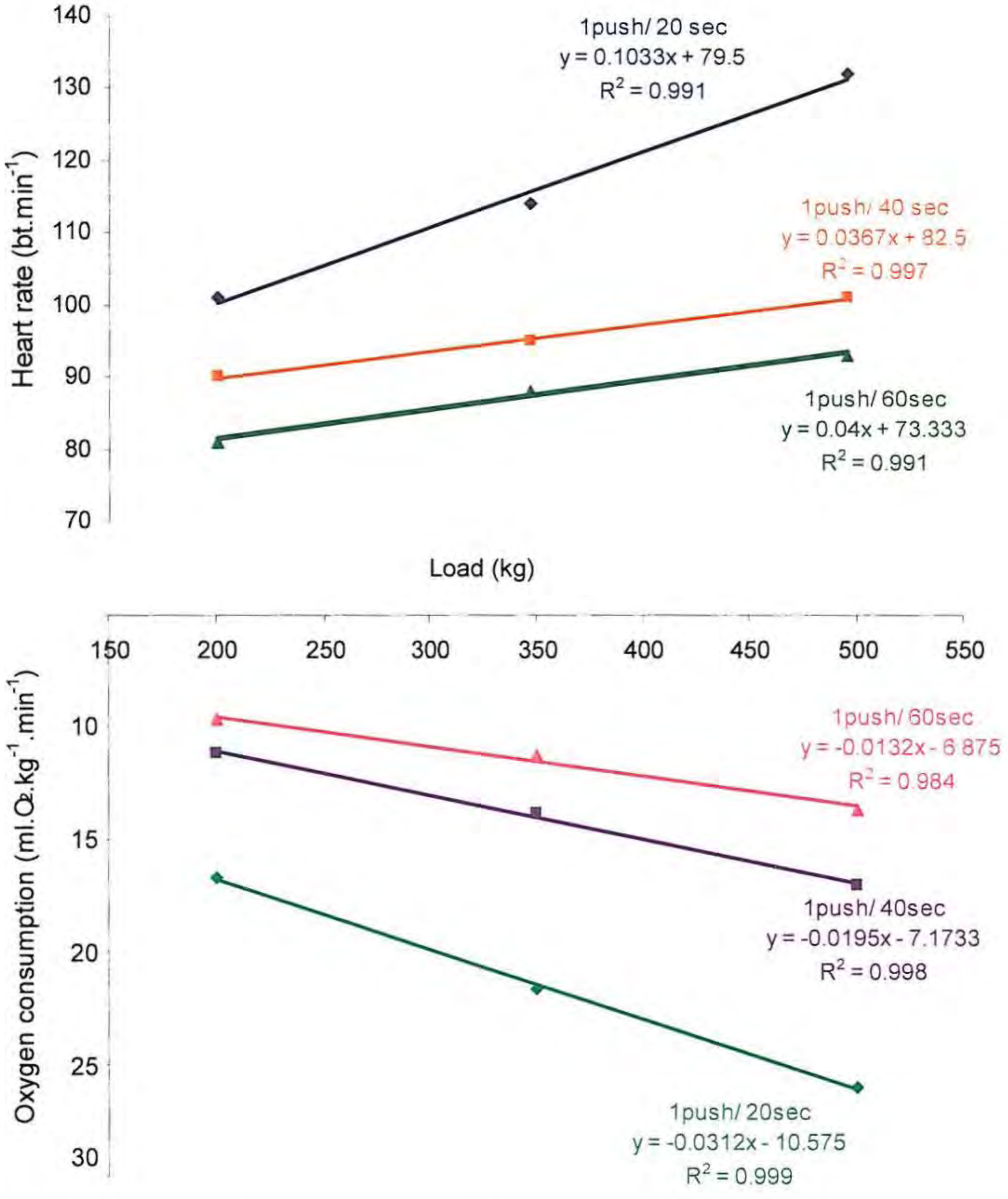

Figure 20: Relationship between load and heart rate/oxygen consumption responses.

Industrial practitioners and ergonomists would be able to predict the oxygen consumption or heart rate responses to any loads between 200kg and 500kg, using the relationship derived in Figure 20. Although both curves show an upward linear relationship to load, the slope of the heart rate curve is steeper, showing the susceptibility of heart rate to increasing changes in load. Figure 20 further emphasises how the highest frequency increases heart rate and $\dot{V}O_2$ compared to the intermediate and slower frequencies. Future researchers should aim to establish these relationships for loads prior to 200kg, and beyond 500kg, once again considering frequency, due to the stop/start nature of pushing tasks. Other task characteristics such as handle height and coefficient of friction need to be included in future studies too.

Energy Cost Attributable to Pushing only

The energy cost of pushing activities can be attributed to walking in addition to pushing. It is useful to be able to determine the relative contribution of the pushing task, over and above walking only. Using the predictive equation of Pandolf **et al.** (1977) it is possible to predict the energy expended by the subjects as a result of walking only. This value could then be compared to the recorded values, to determine the direct physiological impact associated with each load/frequency combination.

The predictive equation:

$$W = 1.5M + 1.5V^2M$$

[where M = body mass (kg), V = walking speed ($m.s^{-1}$) and W = energy expenditure (W)]

was used to establish the energy spent while walking unloaded on a level track. Using the subject's mean body mass it was established that the energy required to only walk at the required speed was $3.40 kcal.min^{-1}$. Figure 21 illustrates that introducing a dynamic pushing task further increases the metabolic demand of the body, with heavier loads and/or higher frequencies placing the body under the greatest physiological strain.

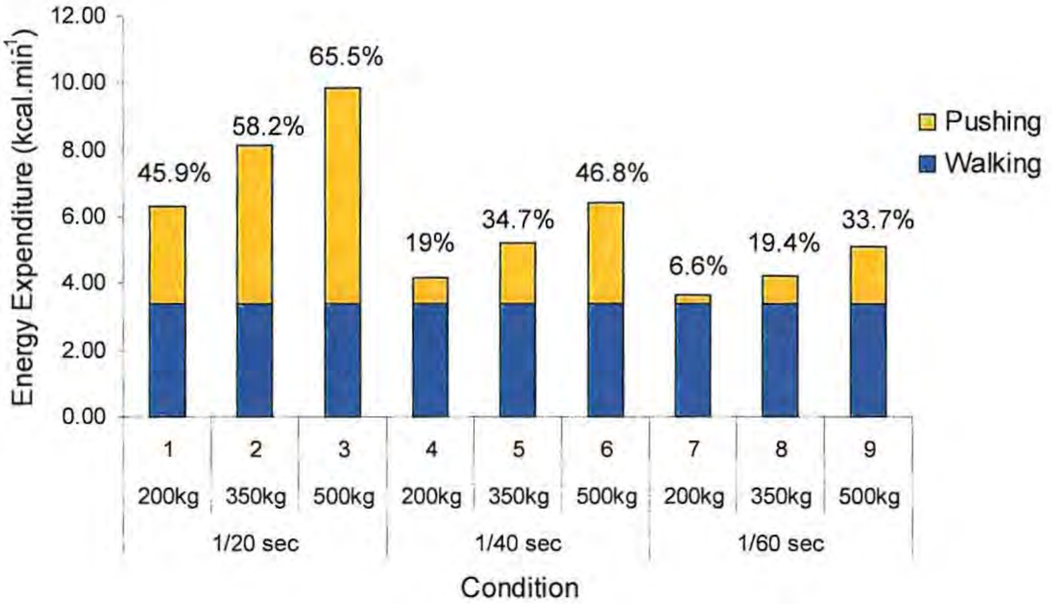

Figure 21: Energy expenditure (kcal.min^{-1}) attributable to walking, and the additional physiological strain due to pushing.

(% show contribution by pushing to overall condition energy expenditure)

The contribution to overall energy expenditure as a result of pushing is evident in Figure 21. The combination of high frequency and heavy load demanded the greatest additional energy output above that due to walking. It is important to note that at loads of as little as 200kg, a high frequency task requires as much energy to be expended as pushing 500kg intermittently, and more than pushing 500kg every 60 seconds. Contrastingly, pushing 200kg once every 60 seconds has very little additional impact over and above that of walking.

The energy required to push a 200kg load once every 40 seconds is similar to the energy required to push a 350kg load every minute, highlighting the integrated effects of load and frequency. Likewise, condition 5 required similar energy expenditure to condition 9. The combination effect is best illustrated by comparing conditions 1-3 to 7-9. It is evident from these findings that the impact of both frequency and load are interlinked and need to be investigated together.

PERCEPTUAL RESPONSES

In addition to biomechanical and physiological responses, an individual's psychophysical response will also determine the efficiency and effectiveness of task performance. The psychophysical approach is thus important, since it is often cognitive processes which may limit the individual's ability to perform tasks optimally, whether in MMH or office based environments. It is well established that an individual's perception of the task demands and body responses differ to that which is physically evident (Straker **et al.**, 1997). This component of the research aimed to establish whether subjects perceived the tasks to be more or less challenging, against the results achieved biomechanically and physiologically, while actually performing the task.

Ratings of Perceived Exertion (RPE)

The RPE scale was used to allow the measurement of subjective responses to the workload experienced by the subject. Both central RPE, representing the subject's cardio-respiratory system and local RPE, representing strain in the upper extremity were measured during the test protocol. Although a linear relationship between heart rate and RPE has been demonstrated with progressively increasing workloads, these reflect individual responses and thus what one individual perceives to be a difficult task may be perceived as less demanding by another. Individual perceptions are likely to differ due to individual motivation and personality, and hence responses were expected to vary substantially (see Table XVI). Condition 3 (500kg, 1/20sec) was significantly greater than all other responses and elicited the highest mean central RPE rating of 13.5 (±1.2) as well as the highest mean local RPE rating of 13 (±1.6). This finding was anticipated as this condition involved the heaviest load at the highest frequency. As the task demands decreased there was an associated decrease in both central and local RPE responses. Condition 7, which combined the lightest load (200kg) and the slowest frequency (1/60sec), elicited the lowest local and central RPE ratings of 8.6 (±1.2) and 8.2 (±1.1) respectively.

Table XVI: Central and local RPE ratings recorded during each condition.

(Means with standard deviations in brackets, %= coefficient of variation)

Load		Central	Local	Central	Local	Central	Local
	500kg	13.5 (1.2) 8.9%	13 (1.6) 12.3%	11.8 (1.5) 12.7%	11.3 (1.5) 13.3%	11.3 (1.5) 13.3%	11.1 (1.7) 15.3%
		3 Heavy		6 Moderate		9 Moderate	
	350kg	11.7 (1.5) 12.8%	10.9 (1.6) 14.7%	11 (1.5) 13.6%	10.2 (1.6) 15.7%	10 (1.5) 15%	9.7 (1.6) 16.5%
		2 Moderate		5 Moderate		8 Light/ Moderate	
	200kg	10.5 (1.5) 14.3%	9.3 (1.5) 16.1%	9.6 (1.4) 14.6%	8.8 (1.5) 17%	8.6 (1.2) 13.9%	8.2 (1.1) 13.4%
		1 Light/ Moderate		4 Light		7 Light	
		1/20sec		1/40sec		1/60sec	
		Frequency					

(detailed ANOVA table can be found in Appendix C)
Shading denotes conditions subjectively rated as 'heavy'.

Conditions 2, 5, 6 and 9 (all statistically similar) could all be classified as moderately taxing according to the responses achieved in the present study. Mean responses of 11.5 (central RPE) and 10.9 (local RPE) would correspond with heart rates of approximately 110bt.min^{-1} which is the suggested maximum limit for any 8-hour working day. As load increased, regardless of frequency, the mean central and local RPE responses increased accordingly. Likewise, as frequency decreased so too did the corresponding mean central and local RPE responses.

Subjects in this study were asked to rate the task as they performed it, and not in respect of whether the task was maintainable for an eight-hour working shift. Only conditions 1, 4, 7 and 8 generated responses which may be deemed as acceptable for extended work periods. However, it must be noted that the high frequency of condition 1, or the heavy load of condition 8 may drive these responses further upwards as the task progresses.

The use of central RPE responses has often been advocated as an attempt to gain an accurate reflection on the task's difficulty, and as such has often been correlated with heart rate responses. Opinions differ as to the suitability of RPE recordings as opposed to direct physiological assessment through heart rate (Olivier and Scott, 1994; Robertson **et al.**, 2000). For numerous lifting activities, correlations have varied between low and moderate. The current study attempted to establish the correlation between central RPE and heart rate (Figure 22) for the current dynamic pushing tasks, since no literature exists which has examined this relationship.

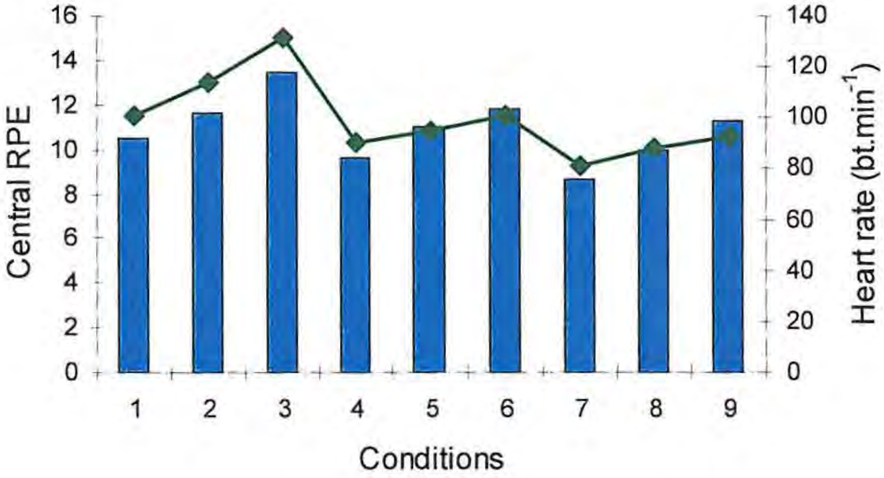

Figure 22: Comparison of working heart rate responses in relation to central RPE responses to each condition.

(Correlation equation relates central RPE to heart rate)

Correlation calculations considering all conditions established a correlation coefficient of 0.807 between central RPE responses and working heart rate. This is a high correlation, indicating that individuals in the current study were reasonably accurate in interpreting their physiological responses and responding appropriately. Subjects in the present study were all well trained and physically active, and thus would be expected to have a good understanding and interpretation of the body's level of exertion. However, Figure 22 shows that the subjects under-estimated their responses to each high frequency condition. This indicates that the subjects responded primarily according to the load as opposed to frequency. RPE responses at the intermediate and slower frequency, with a load of 350kg appear to be closely matched to the recorded heart rate responses. When pushing 500kg at the intermediate or slowest frequency, subjects appear to have then over-estimated the impact of the load, as the RPE responses begin to exceed the recorded heart rate response. This finding suggests that subjects based the majority of their perception on the load they were pushing, and only at the intermediate level did the responses concur closely with the recorded heart rates.

Alternative psychophysical responses used in the current research attempted to establish which areas of the body experienced discomfort while performing the dynamic pushing conditions, together with which areas of the body subjects perceived the exertion to be generated from.

Body Discomfort and Contribution

The body discomfort map and rating scale by Corlett and Bishop (1976) allowed subjects to identify areas of the body in which discomfort was experienced. Due to the number of conditions tested in the current study, and the 27 posterior and anterior locations available on the body discomfort map, Table XVII summarises the findings of the most frequently identified areas, as well as the mean rating the area was given.

Table XVII: Body discomfort ratings for all load/frequency combinations.

Load	**200kg**						**350kg**						**500kg**					
Frequency	**1/20sec**		**1/40sec**		**1/60sec**		**1/20sec**		**1/40sec**		**1/60sec**		**1/20sec**		**1/40sec**		**1/60sec**	
Condition	**1**		**4**		**7**		**2**		**5**		**8**		**3**		**6**		**9**	
	N	**I**	**N**	**I**	**N**	**I**	**N**	**I**	**N**	**I**	**N**	**I**	**N**	**I**	**N**	**I**	**N**	**I**
Quadriceps	1	1	0	0	3	2.1	5	4.3	1	4	2	4	2	3.5	1	3	4	3.1
Hamstrings	2	3	0	0	2	2.5	1	5	2	3	0	0	2	2	1	4	2	3.5
Calves	9	3	6	3.6	7	2.6	10	4.1	14	3.2	11	3.8	8	4.6	11	4.3	10	4
Shoulders	3	2.7	4	2.5	4	2.5	5	3.6	3	3.2	5	3.0	9	4.1	3	3	7	2.8
Biceps	3	3.7	2	3	0	0	2	4	3	3.7	2	2.5	2	4.5	2	4	4	3.8
Triceps	1	3	0	0	0	0	1	6	3	2.8	0	0	0	0	1	5	1	6
Chest	1	3	1	3	0	0	1	5	2	3	0	0	2	3.5	2	3	3	3
Upper back	2	2.5	3	3	2	3.5	3	3.3	2	3.5	4	3.2	6	4.2	4	3.8	3	3
Lower back	5	2.8	6	3.8	4	3.3	5	3.2	7	3.5	7	3.3	5	4.6	7	3.1	7	4
Total ratings	27		22		22		33		37		31		36		32		41	

N= number of ratings for each area; I= mean intensity of discomfort for each area.

Table XVII shows clearly that dynamic pushing tasks require the whole body to be involved in the necessary exertion, as muscle groups in both the lower and upper extremity, as well as posterior and anterior were identified as areas in which discomfort was experienced. It is interesting to note that for all conditions the calf muscles were cited the most frequently as the area of primary discomfort. This finding confirms that future research into dynamic pushing tasks must consider that repetitive pushing and pulling may increase the risk of lower limb injuries. As the load weight increased, more subjects rated the lower back as an area of discomfort. This would be expected as the lower back is bracing the body, and thus separating the dynamic effort of the lower extremity from the predominantly static exertions of the upper extremity. By reporting discomfort in the lower back, subjects in the current study would appear to agree with the numerous researchers who have shown pushing tasks to be related to lower back pain (Hoozemans **et al.**, 1998, Granata and Bennet, 2005; Jung **et al.**, 2005). At the heavier loads, it appears that the shoulders become areas of concern, as increasing numbers of subjects rated the shoulders as uncomfortable. Increases in frequency or load could therefore result in greater shoulder complaints. This is a major concern for ergonomists, as the shoulder joint is a complex joint with multiple planes of movement, and thus critical in allowing the operator to perform any upper body tasks. Injuries to this joint have been increasing with the increasing prevalence of pushing and pulling tasks (Hoozemans **et al.**, 2004), and future research must be aimed at limiting any damage to this crucial joint and muscle complex.

The body discomfort findings of the present study suggest that more focus needs to be placed on the role of the lower extremity in dynamic pushing tasks, and focus must continue on understanding the complexity of the shoulder and its responses under dynamic pushing conditions. However, understanding which areas of the body subjects perceived the effort to be coming from to perform the task would contribute substantially to attempts to fully understand the challenges of a dynamic pushing task. This evaluation aimed at determining which body parts the subjects perceived to be directly responsible for generating the required effort for the dynamic pushing task. Table XVIII shows the areas of the body which were most frequently reported as contributing to the effort.

Table XVIII: Body contribution ratings for all load/frequency combinations.

Load	**200kg**						**350kg**						**500kg**					
Frequency	**1/20sec**		**1/40sec**		**1/60sec**		**1/20sec**		**1/40sec**		**1/60sec**		**1/20sec**		**1/40sec**		**1/60sec**	
Condition	**1**		**4**		**7**		**2**		**5**		**8**		**3**		**6**		**9**	
	N	**I**	**N**	**I**	**N**	**I**	**N**	**I**	**N**	**I**	**N**	**I**	**N**	**I**	**N**	**I**	**N**	**I**
Quadriceps	3	3.4	10	3	9	2.7	10	4.3	9	4.1	7	3.5	12	4.9	14	3.8	11	4.5
Calves	15	3.1	11	2.9	10	2.7	16	4.4	18	3.9	15	3.5	18	5.2	19	4.7	17	4.5
Posterior Shoulders	8	2.6	7	3.8	3	3.3	7	3.4	3	3.8	4	3.9	7	3.8	5	4.4	5	5.4
Anterior shoulders	7	3.4	5	2.4	6	4.4	8	2.6	10	3.8	10	3.9	11	4.9	11	4.4	10	4.1
Biceps	8	3.3	2	3	5	2.2	9	4.1	8	5.1	4	4	6	5.3	6	4.8	9	4.3
Total ratings	**41**		**35**		**33**		**50**		**48**		**40**		**54**		**55**		**52**	

N= number of ratings for each area; I= mean contribution for each area.

Five areas of the body were identified as the main contributors to each pushing effort. These areas include muscle groups from the lower and upper extremity, suggesting that although forward movement and walking is initiated and performed by the legs, the upper body contributes equally to generating the required force and effort to initiate, sustain and stop movement. Generally, as load increased so too did the number of responses and the mean rating, suggesting again that load weight played a major role in influencing subjects' perceptions of the task. Frequency seemed to affect perceptions differently, as a clear pattern is not as obvious, as for some muscle groups the ratings are higher for slower frequencies, despite the load remaining the same.

Increasing load or frequency separately necessitated a larger contribution by the calf muscles, while combined increases brought about even larger contributions. The shoulder complex (anterior and posterior) and biceps are generally responsible for maintaining the static effort involved in controlling and manoeuvring the pallet jack or trolley, and are thus more susceptible to long term fatigue. The contribution of these muscles becomes crucial particularly when the MHD is being stopped or started, as they link the rest of the body to the MHD and thereby absorb a great deal of the force. Therefore load/frequency combinations are critical in determining the perceptions of task demands.

That calves contribute more as load or frequency increase is an important finding for future researchers interested in the muscle activity responses and patterns during dynamic pushing tasks. Electromyographic (EMG) research during pushing tasks is still in its infancy, and to date has tended to concentrate on the shoulder complex and lower back. Therefore further research focusing on the lower extremity is also necessary. The calf muscles are not as large as the quadriceps or shoulder complex muscles, and thus are highly susceptible to injury and damage if required to contribute substantially to all pushing efforts. Equally so, fatigued calf muscles or lower extremity muscles are likely to reduce the response time to hazards which may result in slip, trip and fall accidents.

The relationship between discomfort and contribution is expected to be direct, with the major contributing muscles also experiencing the highest degree of discomfort. The two most prevalent sites of discomfort and contribution for each condition are shown in Table XIX, as a percentage of the total citings per condition.

Table XIX: Areas of body discomfort and contribution (as a % of total citings per condition).

		Body Discomfort	Body Contribution	Body Discomfort	Body Contribution	Body Discomfort	Body Contribution
Load	500kg	Shoulders (25%) Calves (22%)	Calves (33%) Quadriceps (22%) 3	Calves (34%) Lower back (22%)	Calves (35%) Quadriceps (25%) 6	Calves (24%) Lower back (17%)	Calves (33%) Quadriceps (21%) 9
	350kg	Calves (30%) Quadriceps (15%)	Calves (32%) Quadriceps (20%) 2	Calves (38%) Lower back (19%)	Calves (38%) Shoulders (21%) 5	Calves (35%) Lower back (23%)	Calves (38%) Shoulders (25%) 8
	200kg	Calves (33%) Lower back (19%)	Calves (37%) Biceps (20%) 1	Calves (27%) Lower back (27%)	Calves (31%) Quadriceps (29%) 4	Calves (32%) Lower back (18%)	Calves (30%) Quadriceps (27%) 7
		1/20sec		1/40sec		1/60sec	
		Frequency					

Interestingly, only the calf muscles correspond in discomfort and contribution for all conditions, while only condition 2 has both muscle groups appearing as contributors and experiencing discomfort. Table XIX shows that although certain muscle groups are perceived to be responsible for the pushing effort, the discomfort is frequently perceived in other areas of the body, such as the lower back, primarily due to the posture adopted. The quadriceps group along with the shoulders are rated as the most common secondary contributor to the effort, but due to the size and/or nature of these muscle groups, they are not in the top two areas of discomfort. This finding reiterates that smaller muscle groups, such as the calves, are likely to be perceived to experience the most discomfort in pushing tasks. More importantly though, the lower back is at risk of short-term and long-term injury due to its positioning directly between the muscle groups performing dynamic contractions in the lower extremity, and the upper extremity muscles involved in static contractions. Dynamic pushing tasks are thus a risk for the lower back, regardless of load or frequency, since any adverse exposure to strain may have cumulative effects.

INTEGRATED DISCUSSION

Understanding the individual contributions of biomechanical factors, physiological responses and perceptual interpretations to a task provides clarity and greater understanding of the underlying mechanisms driving the demands of any task. However, to fully appreciate the complexity of the task, and to make the most appropriate recommendations to industry it is critical that knowledge gained within each domain is integrated to formulate a complete response.

Table XX integrates the responses from each domain and attempts to identify which conditions are acceptable within industrially developing countries, based on all factors within the current research.

Table XX: Biomechanical, physiological and psychophysical responses to each load and condition.

	200kg			350kg			500kg		
PI	212.8 N			**293.7 N**			**366.3 N**		
AS	50.0 N			**89.2 N**			**125.6 N**		
PE	*137.8 N*			*202.2 N*			*246.4 N*		
	1/20sec	**1/40sec**	**1/60sec**	**1/20sec**	**1/40sec**	**1/60sec**	**1/20sec**	**1/40sec**	**1/60sec**
HR	101	90	81	**114**	95	88	**132**	101	93
$\dot{V}O_2$	16.71	11.15	9.67	**21.68**	13.85	11.21	**26.06**	17.02	13.64
E%max	**36.5**	24.3	21.1	**47.3**	30.2	24.5	**56.9**	37.2	29.8
EE	6.29	4.20	3.64	**8.14**	5.21	4.22	**9.85**	6.39	5.13
cRPE	10.5	9.6	8.6	11.7	11	10	**13.5**	11.8	11.3
lRPE	9.3	8.8	8.2	10.9	10.2	9.7	**13.0**	11.3	11.1

Where: PI= peak initial forces, AS= average sustained forces, PE= peak ending forces.
HR= heart rate (bt.min^{-1}), $\dot{V}0_2$= relative oxygen consumption (mlO$_2$.kg^{-1}.min^{-1}),
E%max= estimated percentage of maximum, EE= energy expenditure (kcal.min^{-1})
CRPE= central Rating of Perceived Exertion, LRPE= local Rating of Perceived Exertion.
(**Red font** identifies responses exceeding guideline recommendations, while orange font identifies marginal conditions; *italics* denotes variable for which no guidelines exist)

The results illustrated above clearly demonstrate the effect of load and frequency on responses recorded in each domain. Increasing loads required increased forces to be generated in the initial, sustained and ending phases of the pushing task. The increasing force requirements have a concomitant effect on the physiological responses. Higher loads coupled with higher frequencies required individual responses which were beyond the recommended guidelines of previous researchers. Alternatively, intermittent to infrequent pushing of 'lighter' loads is more likely to require levels of exertions well within the recommended guidelines.

Understanding the relationship between the biomechanical and physiological responses is imperative. More importantly, it must be acknowledged that it is not the load which is important, but rather the forces required to move the load. Thus it is the interaction of exerted forces and frequency which are placing strain on the individual necessitating increased cardiovascular output. Regardless of load, maintenance and coefficient of friction, it is the forces required that determine both biomechanical effort and physiological strain. Therefore measurement of these forces is of paramount importance. Industry can measure the required force output through low cost means, and equate the forces required to likely physiological responses, taking cognisance of the frequency at which the task is performed. This would then factor in poor maintenance or alternative MHD design and encourage engineers and designers to limit the required forces through optimum design. It thus reduces the problem of having to assess complex interactions, to a simple interaction between force and heart rate or $\dot{V}O_2$.

Each of the forces exerted when pushing the 200kg load fell within existing recommendations, and resulted in physiological responses that are deemed manageable by the majority of a male working population. At higher frequencies though, the potential exists for physiological responses to rise above the recommended limits. When pushing the 350kg and 500kg loads, the initial and sustained forces exceeded current guidelines, and may pose biomechanical risk to the operator. In addition, all three forces contributed towards elevated physiological responses at higher frequencies, making the task unsuitable for extended work. The forces exerted when pushing 500kg created unacceptably high physiological and perceptual responses when exerted at the highest frequency. At lower frequencies, all the forces relate to physiological responses that would be considered acceptable to the majority of a male working population, and thus it is the forces exerted which present the greatest risk to the operator.

Figure 23 shows the relationship between load and oxygen consumption in absolute terms and relative to the load being pushed.

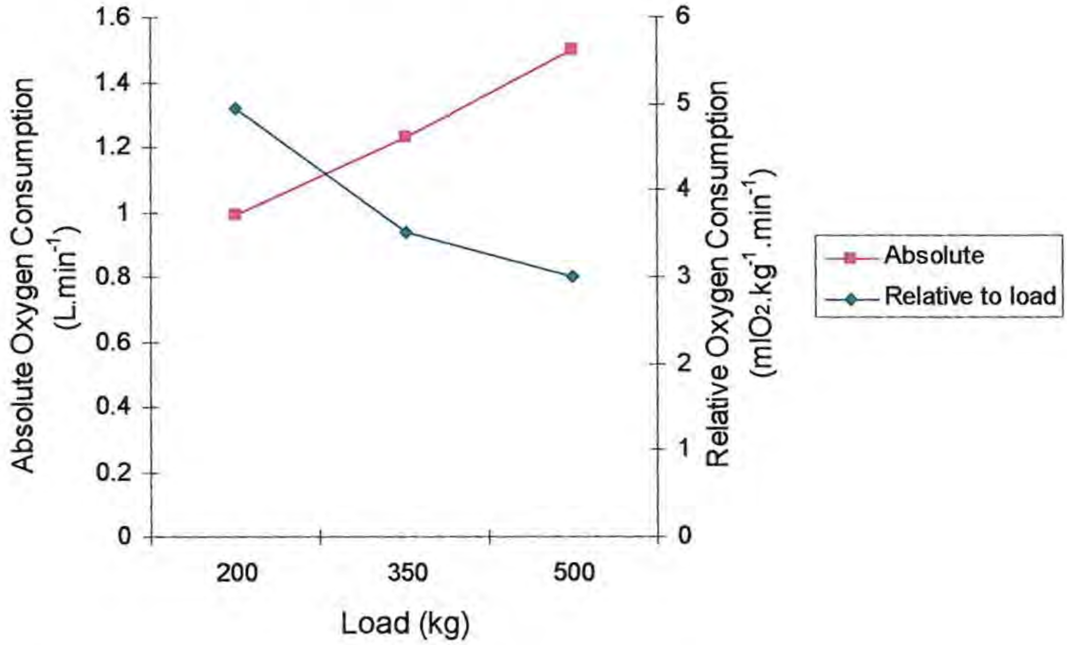

Figure 23: Absolute and relative oxygen consumption in relation to load pushed.

Absolute oxygen consumption increases as load increases, while the relative oxygen consumption decreases with the same increase in load. This important finding shows that if a dynamic pushing task is going to be performed infrequently, it may be of greater benefit from a $\dot{V}O_2$ perspective to move heavier loads, since the relative oxygen consumption per kilogram moved is less at higher loads. If the task is going to be performed more frequently though, the oxygen consumption values will increase beyond acceptable limits. This important finding justifies the use of Manual Handling Devices (MHDs) for the manipulation of heavier loads moved more frequently.

The average sustained forces are the forces most expected to contribute towards elevated physiological and perceptual responses due to the increased duration for which they are exerted. Table XX shows that if an individual is required to exert sustained forces in excess of 89.2N, not only is the musculature of the body exposed to strain, but if the task is performed frequently, individuals are going to require 8.14kcal.min^{-1} which will lead to additional physiological fatigue. If the sustained forces increase to 125.6N or more, the likelihood of biomechanical and physiological problems increase further, with energy expenditure at higher frequencies possibly exceeding 56% of $\dot{V}O_{2max}$ or 9.85kcal.min^{-1}. Therefore if the load requires 125N of force in order to be moved, frequencies higher than once per minute are likely to lead to fatigue while even forces of 89N are of concern at higher frequencies.

Figure 24 demonstrates the relationship between average sustained forces and oxygen consumption. The positively related linear relationship shows a correlation in excess of 0.99, which demonstrates a strong relationship between these variables. This result confirms that simple measures of average sustained force required to manipulate a load by pushing may provide sufficient detail to make accurate assumptions as to the likely physiological cost of performing that task at intermittent to high frequencies.

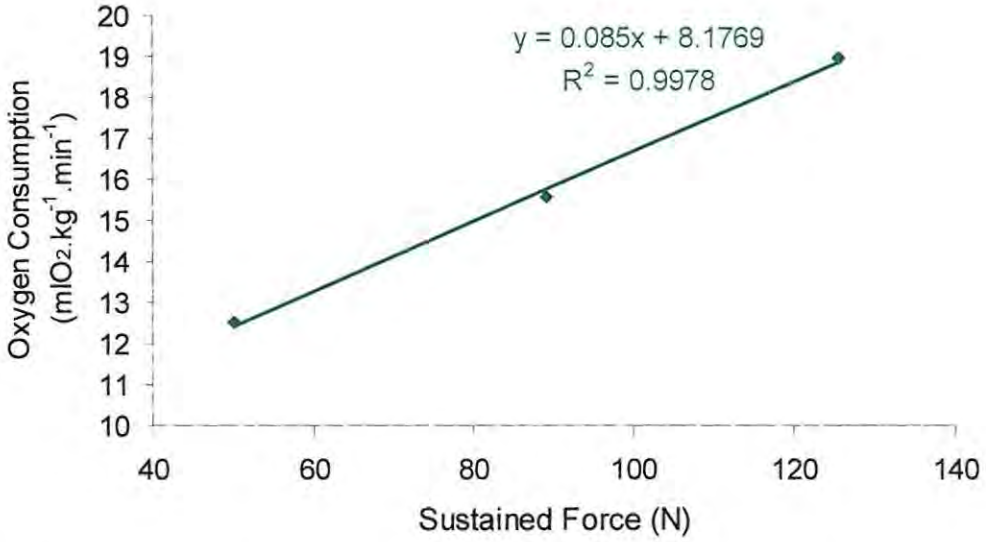

Figure 24: Relationship between average sustained force and oxygen consumption (mlO$_2$.kg^{-1}.min^{-1})

The combination of high sustained forces and elevated physiological responses contribute towards the increased perceptual response, driving up the perceptions of cardiovascular and muscular strain. When the exerted forces are within the guidelines proposed, as with the initial and sustained forces pushing 200kg in the current study, it can be seen that subsequent physiological and perceptual responses are well within the acceptable limits for individuals exposed to those strains for eight hours per day.

It becomes more challenging to relate the initial or ending forces to energy expenditure, as these forces are exerted for short periods of time; however, the elevated force demands during these stages of the exertions are likely to contribute towards elevated heart rate responses, and, over time, elevated energy cost. Therefore future research needs to address this relationship in order to develop holistic guidelines for the performance of dynamic pushing tasks.

Due to the nature in which the forces exerted in the initial, sustained and ending phase of the pushing task were measured and recorded, it is not possible to graphically depict a statistical matrix, as the result would replicate Table VII. However, it is of value to researchers to be able to interpret the integrated results of the physiological and perceptual responses, as shown in Table XXI.

Table XXI: Gait, physiological and perceptual responses (and percentages) significantly different between the nine load/frequency conditions.

Condition	1	2	3	4	5	6	7	8	9
1		57	71	43	29	14	57	57	29
2	HR, $\dot{V}O_2$, EE, LRPE		71	71	43	43	71	57	43
3	HR, $\dot{V}O_2$, EE, LRPE, CRPE	HR, $\dot{V}O_2$, EE, CRPE, LRPE		86	86	86	86	86	86
4	HR, $\dot{V}O_2$, EE	HR, $\dot{V}O_2$, EE, CRPE, LRPE	SL, HR, $\dot{V}O_2$, EE, CRPE, LRPE		43	71	0	14	43
5	$\dot{V}O_2$, EE	HR, $\dot{V}O_2$, EE	CAD, HR, $\dot{V}O_2$, EE, CRPE, LRPE	$\dot{V}O_2$, EE, CRPE		29	71	20	0
6	LRPE	HR, $\dot{V}O_2$, EE	CAD, HR, $\dot{V}O_2$, EE, CRPE, LRPE	HR, $\dot{V}O_2$, EE,CRPE, LRPE	$\dot{V}O_2$, EE		71	71	29
7	HR, $\dot{V}O_2$, EE, CRPE	HR, $\dot{V}O_2$, EE, CRPE, LRPE	CAD, HR, $\dot{V}O_2$, EE, CRPE, LRPE	-	HR, $\dot{V}O_2$, EE, CRPE, LRPE	HR, $\dot{V}O_2$, EE, CRPE, LRPE		14	71
8	CAD, HR, $\dot{V}O_2$, EE	HR, $\dot{V}O_2$, EE, CRPE	CAD, HR, $\dot{V}O_2$, EE, CRPE, LRPE	CAD	$\dot{V}O_2$, EE	HR, $\dot{V}O_2$, EE, CRPE, LRPE	LRPE		29
9	$\dot{V}O_2$, EE	HR, $\dot{V}O_2$, EE	CAD, HR, $\dot{V}O_2$, EE, CRPE, LRPE	$\dot{V}O_2$, EE, LRPE	-	$\dot{V}O_2$, EE	HR, $\dot{V}O_2$, EE, CRPE, LRPE	$\dot{V}O_2$, EE	

Variables in the lower half of the matrix indicate variables which **are** significantly different between conditions.

Numbers in upper half of matrix are percentages (%) of variable responses that are different (as identified above).

The results illustrated above clearly demonstrate the effect of changes in load/frequency on subjects' physiological and perceptual responses. During any dynamic pushing task, load and frequency interact to create task demands which require physiological and perceptual responses from the human operator. The interaction of these two variables is such that an increase in either or both will ultimately raise the requirements of the task. Table XXI shows evidently that combinations involving heavy loads and high frequencies placed the greatest demand on the operator.

CHAPTER V

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

INTRODUCTION

MMH persists in IDCs as a primary means of manipulating the position of objects and loads within the workplace, consequently musculoskeletal injuries continue to plague this working population (Jaffry and O'Neill, 2000). Due to the awareness regarding lifting and carrying as hazardous manual materials handling techniques, many industries have begun to introduce manual handling devices (MHDs), such as carts and trolleys (Hoozemans **et al.**, 1998). These MHDs have dramatically reduced the demands placed on the operator as a result of lifting and carrying, but concomitantly, have increased the necessity for pushing and pulling efforts within the workplace (Schibye **et al.**, 1997). Despite the importance and prevalence of pushing and pulling in industry, relatively little attention has been focused on this area in prior studies (de Looze **et al.**, 2000).

Ergonomic studies have shown that pushing activities exist in several occupations and industries (van der Beek **et al.**, 2000), yet there is limited research on the potential injury risks associated with pushing. Similar to repetitive lifting or lowering of a load, pushing is linked with considerable isometric muscle activity in the trunk and upper extremities of workers, leading to localised fatigue and increased cardiovascular stress (Hoozemans **et al.**, 1998). In addition, dynamic activity in the lower extremity is contributing further towards muscular and cardiovascular fatigue, while the forces required initiating, sustaining and ending pushing tasks are likely to contribute to acute and chronic muscular and skeletal injuries. The limits and potential risks of pushing tasks have still to be clearly established and defined, while research needs to address the biomechanical and physiological effects of pushing tasks, and substantiate these findings.

This study undertook a multi-disciplinary approach to investigate nine combinations of load and frequency in a dynamic pushing task using an industrial pallet jack, to determine the biomechanical, physiological and psychophysical impact the task would have on the human operator. It is therefore anticipated that this research will contribute substantially to the existing knowledge regarding human responses to dynamic pushing tasks, as evidenced and performed *in situ*. The understanding and insight gained through this research will increase the awareness of human responses to varying load/frequency combinations during dynamic pushing.

SUMMARY OF PROCEDURES

The present study was conducted in a laboratory environment at the Department of Human Kinetics and Ergonomics at Rhodes University. Nine experimental pushing conditions formed the basis of the study, with subjects required to push an industrial pallet jack with three loads (200kg, 350kg and 500kg) at three frequencies (1/20seconds, 1/40seconds and 1/60seconds), at a controlled speed of 3.6km.h^{-1} over 14 metres on a coefficient of friction controlled walkway for a duration of six minutes. The loads and frequencies were selected after numerous industrial visits, a thorough review of the current literature and extensive pilot studies.

A sample group of thirty healthy male subjects with a mean age of 21.87 years, body mass of 79.10kg and a mean stature of 1815mm (stature range extended between 1750mm and 1900mm). Each subject was required to perform all nine experimental conditions, requiring subjects to attend three one-hour sessions, in addition to habituation, in which three conditions were randomly tested. All testing was carried out in the morning to account for circadian rhythms. Habituation sessions were conducted prior to experimentation, and subjects' demographic data, including age, mass and stature were collected at these sessions.

Primary biomechanical research concentrated on exerted forces in the initial, sustained and ending phase of a pushing task, and thus frequency was not a contributing factor. Force exertion during all three push phases was measured using the Chattillon Hand-Held Dynamometer, and was carried out prior to the commencement of the six-minute protocol. Once two full pushes had been satisfactorily completed for each load, subjects commenced with a six-minute protocol in which the load/frequency combination stayed constant, as did walking speed and distance moved. Additional biomechanical interest lay with the gait pattern responses during the sustained phase as a result of load and frequency changes. Physiological interest lay in the heart rate, oxygen consumption and energy expenditure responses of the subjects, while RPE, body discomfort and body contribution feedback provided perceptual insight. During the protocol, heart rate and oxygen consumption ($\dot{V}O_2$) were recorded using the K4b^2 ergospirometer, while digital video run through Silicon Coach Pro recorded subjects' gait pattern responses, from which cadence and stride length were analysed. Energy expenditure responses (kcal.min^{-1}) were then derived from the $\dot{V}O_2$ measurement. In addition, RPE was recorded after the fourth and sixth minutes, while body discomfort and body contribution were recorded on completion of each condition.

Basic descriptive statistics relative to the variables assessed were computed, providing general information concerning the sample. Student T-tests were used to determine whether the responses of the fourth minute differed from those in the sixth minute. Thereafter, two-way ANOVAs were utilised to assess the impact of load or frequency individually, while one-way ANOVAs were used to determine whether there were any significant differences between the nine experimental conditions.

SUMMARY OF RESULTS

The results obtained in the present study provide valuable insight into the biomechanical, physiological and perceptual demands of a dynamic pushing task. More importantly it quantifies the responses of individuals from a developing country, and highlights the strain present whilst performing a common industrial task.

Biomechanical responses

The force exerted in the initial, sustained and ending phase of a dynamic pushing task were the primary variables of biomechanical interest. The peak initial forces required to overcome the pallet jack and loads' inertia ranged between 212.8N (±45.3) and 366.3N (±47.0). These forces represent concern for ergonomists as forces above 225N are considered beyond the acceptable range for human operators. Therefore loads greater than 350kg may pose a risk of injury to operators required to move them on a regular basis. Although these forces are only exerted within the first 3-5 seconds of the task until inertia is overcome, they are of sufficient magnitude to pose both an acute and chronic risk to the operator.

The average sustained forces were of key interest to the current study, as these forces are maintained for extended periods of time, and are thus likely to be responsible for increasing the cardiovascular and pulmonary output. The average sustained forces ranged from 50N (±8.8) to 125.6N (±17.6). Although this may not seem like excessive force requirement, these forces are required to be exerted throughout the push duration. It has been recommended that sustained forces should not exceed 89N, and thus, heavy loads, poor maintenance or high coefficient of friction are likely to increase the forces into the range beyond that deemed acceptable for extended work. The forces required to maintain movement of loads greater than 350kg are thus likely to require sustained forces beyond that which are acceptable to human operators.

The peak ending forces measured provided valuable insight into the demands associated with overcoming an object's momentum, and bringing the object to rest. This phase of a pushing task is under-researched, and as such no guideline criteria exist. It was found that the peak ending force ranged between 137.8N (±44.4) for loads of 200kg, and 246.4N (±58.1) for loads of 500kg, and represented approximately 6% of the load pushed and 67% of the forces required to initiate movement. The forces recorded when ending a pushing task are measured as peak values, and thus may be responsible for acute injury. However, they are lower than the peak initial forces and thus fall within safe limits of the guidelines for initial forces. Unfortunately, since the ending force is actually a pulling action, the technique differs to that used to initiate movement and could therefore not be comparable. Therefore these forces need further examination.

Investigation into the nine recorded forces (three initial, three sustained and three ending) revealed that significant differences arose between the majority of the forces. The lowest force recorded was the sustained force at 200kg (50N), while the initial force at 500kg (366.3N) had the highest mean recorded force. Similar responses were recorded between initial (200kg) and ending (350kg), as well as between ending (200kg) and sustained (500kg). All other responses were significantly different from each other. Significant differences were established between the initial, sustained and ending forces for each load (see Table VII), indicating that each stage of the task differs in its contribution to musculoskeletal stress. This finding highlights the importance of investigating each phase of the pushing task in isolation before drawing conclusions. Furthermore this finding substantiates the need for further research into the role of sustained and ending forces in musculoskeletal injuries related to dynamic pushing tasks.

It was hoped that an introductory analysis of gait pattern changes would shed insight to the adaptations made by human operators to cope with changes in task demands. However, gait pattern responses were not found to differ significantly between conditions, with both stride length and cadence recording minimal statistically different responses. It needs to be noted that these responses were not compared to "natural" gait patterns, which may have been different.

Physiological responses

Of primary interest to the current research were the cardiovascular responses associated with different load/frequency combinations whilst performing the dynamic pushing task. Physiological cost related to pushing and pulling in industry is under - researched, particularly the 'stop-start' pushing and pulling tasks. Each physiological variable showed a similar response pattern, with the combination of the heaviest load and quickest frequency requiring the greatest physiological output, whilst the lowest load, slowest frequency condition recorded the lowest heart rate, $\dot{V}O_2$ and energy expenditure results.

Heart rate responses ranged between 81bt.min^{-1} and 132bt.min^{-1}, with condition 2 and condition 3 both requiring mean heart rates in excess of the recommended 110bt.min^{-1} guideline (Brouha, 1967). These combinations are therefore likely to contribute to acute and chronic fatigue, resulting in an increase in accidents, and are thus not recommended. Load played an increasingly important role in the physiological cost of the task, as frequency increased. Significant differences were established between the highest frequency and the intermediate and slowest frequency for all loads, but no significant differences between the intermediate and slowest frequency were found. This finding implies that an individual's heart rate responses are similar when the task is performed once every 40 seconds or less. The findings of the current study concur with previous research by van der Beek **et al.** (1999), and suggest that the impact of frequency on physiological demands is dependent on the load being moved, and that these two critical task characteristics need to be investigated together rather than in isolation.

The highest mean oxygen consumption recorded was 26.06ml.O_2.kg^{-1}.min^{-1} during condition 3, while condition 7 recorded the lowest mean $\dot{V}O_2$ of 9.67ml.O_2.kg^{-1}.min^{-1}. Significant differences ($p<0.05$) were established between all frequencies at each load, where the $\dot{V}O_2$ responses at the highest frequency were 72.8%, 93.3% and 91% higher than the slowest frequency for the 200kg, 350kg and 500kg loads respectively. At the intermediate and slower frequency, the percentage increase in $\dot{V}O_2$ between 200kg and 350kg loads is smaller than at the highest frequency; however, the opposite was evident for the change in load from 350kg to 500kg. This suggests that at high frequencies both load and frequency are important contributors to $\dot{V}O_2$ but load drives up the response at slower frequencies. Conditions 2 and 3 exceeded recommended guidelines, thus making them unacceptable tasks physiologically, while conditions 4, 7 and 8 were classified as light according to the McArdle **et al.** (2001) classification. The other conditions were classified as moderate and would therefore be acceptable tasks provided that no biomechanical or perceptual tolerances were exceeded. The $\dot{V}O_2$ findings of the current study confirmed expectations that continuous pushing elicits different responses to 'stop-start' pushing, as results were considerably different to some comprehensive previous literature (Wyndham and Heyns, 1967). This research recommends that future investigations consider the direct impact of speed on all responses.

Energy expenditure was derived from oxygen consumption responses, and as such the results have identical statistically significant findings, with significant differences ($p<0.05$) arising due to frequency at each load, while differences arose due to load between the quickest and intermediate frequencies. The greatest energy expended occurred during the heavy load, high frequency condition, and elicited a mean response of 9.85kcal.min^{-1}, while the opposite condition (lightest load, slowest frequency) resulted in the lowest mean response of 3.64kcal.min^{-1}. Decreases in frequency were accompanied by decreases in energy expenditure, while both load and frequency played crucial roles in determining the energy required to perform each condition, with increases in load requiring increased energy output. At the quickest frequency a 150% increase in load resulted in a 56.6% increase in energy cost, with increases of only 52.1% and 40.9% at the intermediate and slowest frequencies. These findings reiterate the increasing importance of load as frequency increases, while the impact of load is more pronounced at loads above 350kg. Conditions 4, 7 and 8 were again classified as light, with conditions 2 and 3 being classified as heavy to very heavy. An important finding of this study was that even loads of 500kg pushed once every minute could result in a moderately taxing task. This indicates that in industry load must be carefully controlled, since even at slow intermittent frequencies and under optimal conditions, high levels of energy could be expended.

Strong positively linear relationships ($r^2= 0.98$) were established between heart rate and oxygen consumption and the subsequent predictive capacity showed a mean under - prediction of 1.4%. Alternatively, very strong positively linear relationships with correlations above 0.98 were established between load and $\dot{V}O_2$ as well as load and heart rate. This important finding would provide practical benefit to industry for loads between 200kg and 500kg. Due to the stop start nature of the current research, it was likely that it was the forces exerted, in each of the initial, sustained and ending phases were of more critical importance influencing the physiological output, as opposed to the load itself.

Psychophysical responses

Psychophysical evaluation provided valuable insight to the subjective ratings of each condition. Central and local ratings of perceived exertion (RPE) were used to determine the extent to which the cardiovascular system and upper extremity were being taxed by the condition. Condition 3 reported the highest central RPE of 13.5 (±1.2) and local RPE of 13 (±1.6). These responses were significantly greater than responses to any other condition. Condition 7 recorded the lowest mean central and local RPE of 8.6 and 8.2 respectively. A correlation of 0.807 was established between mean recorded heart rates and mean reported central RPE, indicating that the subjects were able to interpret their physiological response to the task relatively accurately.

Body discomfort and body contribution responses were invaluable in gaining further understanding of the areas of the body utilised to perform a dynamic pushing task. Body discomfort results showed that both the upper and lower extremity are used extensively when pushing, with the calf muscles reported to experience the most discomfort. As load increased so did reports of lower back discomfort. This finding substantiates previous pushing research by Hoozemans **et al.** (1998) that the lower back is a vulnerable area during pushing tasks. Of particular interest was the extent to which the shoulder complex was rated as experiencing discomfort, as this joint poses concerns to ergonomists investigating shoulder complaints due to the intricate nature of its potential movement and the contributing musculature. Body contribution aimed to establish which areas of the body subjects perceived the effort to be coming from to generate and maintain movement. Calve muscles were rated most frequently, followed by the shoulder muscles and biceps. Generally, an increase in load resulted in an increase in responses and mean rating, suggesting that load played a large role in determining the subject's perceptions of the task.

HYPOTHESES

Biomechanical hypotheses

The hypotheses (1a and 1b) are discussed with reference to load only, as frequency was not expected to alter the force responses of the task. Hypothesis 1c considers the impact of both load and frequency on gait pattern responses. It was expected that increasing load would increase the force requirements at all phases (initial, sustained and ending) of the dynamic pushing task. Changes in load and frequency were anticipated to alter the stride length and cadence responses of subjects.

Hypothesis 1(a):

This hypothesis stated that no difference existed between all the exerted forces. This hypothesis is rejected as 94.5% of the forces were significantly different to each other. Only two pairs of forces were found to be statistically similar to each other.

Hypothesis 1(b):

The hypothesis under test was that there would be no difference between the initial, sustained and ending forces exerted for each load. This hypothesis is rejected as significant differences arose between the peak initial, average sustained and peak ending forces for each load.

Hypothesis 1(c):

This response is tentatively retained since the majority of results supported the hypothesis that no significant difference arose in gait pattern responses as a result of changes in the load/frequency combination. Cadence revealed significant differences between only 19% of conditions while stride length was only found to be significantly different in 3% of conditions.

Physiological and Perceptual Hypothesis

As the physiological and perceptual responses were recorded for nine conditions, so the rejection or tentative acceptance of the hypothesis will be based on the majority of significant responses which have been identified.

Hypothesis 2:

With respect to the physiological responses, the null hypothesis is rejected. Statistical analysis revealed significant differences in the majority of the heart rate (64%), oxygen consumption and energy expenditure (86%) responses.

Hypothesis 3:

In respect of the third hypothesis dealing with perceptual responses, the results similarly require rejection of the null hypothesis for local RPE responses with 53% of responses showing significant differences. With regards to the 'central' RPE responses the null hypothesis is tentatively retained as 50% of responses reported a significant difference. Due to the subjective nature of RPE responses, these findings are not beyond the realm of possibility.

CONCLUSIONS

These results emphasise the need to carefully consider all the possible contributing factors to a dynamic pushing task. Researchers and practitioners must be aware of the demands on the human operator during all phases of a dynamic pushing task, and recognise the subsequent physiological and perceptual strain associated with the task. The information obtained in this study is important in establishing baseline data regarding forces required when manipulating loads on industrial pallet jacks, in addition to the associated physiological and perceptual responses related to the dynamic pushing task, as load and frequency change.

Recognising the increasing prevalence in the use of manual handling devices (MHD), such as manual pallet jacks, in industries worldwide, understanding of the forces required to initiate movement from stationary, sustain the movement in a controlled manner, and ultimately bring the MHD to a stop are fundamental. High forces can be associated with acute and chronic muscular injury, especially when exceeding the recommended guidelines. In addition to the high forces associated with a dynamic pushing task of loads above 350kg, is a related increase in the physiological cost of the task, and subjective rating of the task demands as the task is performed more frequently. Thus dynamic pushing tasks of loads above 350kg, performed frequently, expose the operator to elevated risks of short and long term fatigue and injury, possibly leading to mistakes and accidents within the workplace.

The interaction effect of load and frequency, as two variables influencing pushing tasks demands, are emphasised in the current research. These factors need to be studied together in order to fully understand the extent of demand placed on the human operator performing the task. Load and frequency integrate and contribute to increased biomechanical, physiological and perceptual demands during pushing tasks, and thus need to be controlled in order to ensure that an operators safety and well-being is maintained.

RECOMMENDATIONS

Future investigations into the biomechanical, physiological and perceptual responses to changes in load and frequency during dynamic pushing should consider the following recommendations:

1) Future research needs to consider the broad extent of loads pushed in industry as well as the range of frequencies and speeds at which this is done. Greater and lesser loads, as well as different frequencies and velocities must be tested

to continue formulating an idea of the interaction effects of load and frequency on dynamic pushing tasks.

2) Maintenance of pallet jacks as well as the surface on which they are used must be at an optimum in order to assist in reducing the necessary forces, and operators must be matched to tasks of which they are physically capable.

3) Due recognition must be given to the role of pulling in industry, and similar research conducted on the holistic responses associated with pulling.

4) Gait pattern responses whilst pushing need to be evaluated against natural walking patterns in order to determine the role of gait in stability and prevention of slip, trip and fall accidents.

5) Determining female responses under dynamic conditions will be invaluable in shaping guidelines regarding maximum acceptable loads and frequencies for pushing activities. It is important that this research be conducted in IDCs, since cultural and societal differences between female populations are well recognised.

6) The impact of load on muscle activity in the upper and lower extremity musculature must be considered. EMG analysis to determine the extent of contribution from the lower limbs and the shoulder complex will help alleviate confusion as to the contributing musculature, and may assist in prevention of injury to these areas.

7) Future research should focus on the interplay between posture and the risk of musculoskeletal disorders as well as slip, trip and fall accidents which have been frequently linked to dynamic pushing tasks.

8) Due to the difficulty in extrapolating findings from the laboratory into workplace situations, findings of the current research need to be evaluated under workplace conditions, and future recommendations carried out with direct *in situ* analysis.

The following practical applications for the use of dynamic pushing as a sustainable manual materials handling task are suggested:

Loads requiring forces greater than the recommended limits need the frequency of task performance to be limited, (depending on the distance), in order to reduce the physiological costs.

Low cost measurement of the average sustained forces required to keep a load moving can be accurately used to determine the likely physiological strain to which the operator is to be exposed (see Figure 19, page 123).

However, should heavy loads have to be moved, it is of physiological advantage to move greater loads less frequently, than lighter loads more frequently (see Figure 22, page 137). The high required forces likely to move such loads can be offset by using two operators, while utilising a well maintained MHD on a surface conducive to safe and efficient movement.

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Note: Asterisked citations * are secondary sources. These were not directly consulted and are referenced as fully as primary sources, indicated in brackets, permit.

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APPENDIX A: GENERAL INFORMATION

Administrative Checklist
Equipment Checklist
Experiment Schedule
Letter to Subject
Subject Informed Consent

ADMINISTRATION CHECKLIST

FAMILIARISATION

Before subject arrives:

- Letter of information and informed consent ready with pens and clipboards
- Perceptual scales and instructions to subject explanations ready
- Subject data sheets ready
- Experimentation timetable ready and available

Once subject arrives:

- Introduction to the research
- Letter of information and questions
- Informed consent and questions
- Explanation of perceptual scales and questions
- Demographic and anthropometric measures collected
- Subject habituated to pallet jack, walkway and $K4b^2$
- Time selection for data collection sessions

DATA COLLECTION

Before subject arrives:

- Ensure that the perceptual scales, stop watch and data collection sheets are ready along with stationary.
- Ensure that correct randomisation sequence is chosen.
- Run through process with assistants to ensure that everyone understands procedures.

Once subject arrives:

- Ensure that subject is free from injury and/ or illness.
- Check that subject is familiar with perceptual scales and required procedures.

EQUIPMENT CHECKLIST

FAMILIARISATION

Before subject arrives:

- K4b^2 is set up and calibrated
  - 4 different size face masks
  - 3L syringe
  - Harness for K4b^2
  - Mixed gas cylinder
  - Computer with additional storage capacity
- Pallet jack with pallets and loads
- Chatillon Dynamometer with laptop computer
- Polar heart rate monitor strap
- Perceptual scales and explanations ready
- Anthropometers, Toledo scale and stadiometer ready

Once subject arrives:

- Stature, mass and anthropometric measures
- Explanation of perceptual scales
- Fitting of Polar heart rate strap
- Fitting of harness and face mask for K4b^2
- Chatillon Dynamometer and laptop computer running

DATA COLLECTION

Before Subject arrives:

- K4b^2 is set up and calibrated
  - 4 different size face masks
  - 3L syringe
  - Mixed gas cylinder
  - Computer with additional storage capacity
  - Subject information is stored
- Pallet jack with pallets and loads ready
- Chatillon Dynamometer with laptop computer ready
- Digital video camera with laptop computer ready
- Perceptual scales

Once subject arrives:

- Fitting of Polar heart rate strap
- Confirm understanding of perceptual scales
- Fitting of harness and face mask for K4b^2
- Final calibration of K4b^2

EXPERIMENT SCHEDULE

Session 1: Familiarisation *(6 people at a time)*

- Introduction to the research
- Letter of information and questions
- Informed consent and questions
- Explanation of perceptual scales
- Demographic and anthropometric measures
- Subject habituation to pallet jack, walkway and K4b^2
- Time selection for data collection sessions

Session 2, 3 and 4: Data collection *(2 people at a time)*

- Welcome and questions
- Perform three conditions, randomised, alternating between subjects to allow rest and recovery

LETTER TO SUBJECT

Dear ______________________________

Thank you for volunteering to be a subject in my Masters research project entitled:

THE IMPACT OF LOAD AND FREQUENCY ON THE BIOMECHANICAL, PHYSIOLOGICAL AND PERCEPTUAL RESPONSES TO DYNAMIC PUSHING.

The focus of the present study is to investigate the impact of different load/frequency combinations on the biomechanical, physiological and psychophysical responses of individuals performing dynamic pushing tasks.

The main objective of the study is to establish load/frequency combinations which minimise the biomechanical and physiological impact on the body during dynamic pushing. This should allow the researcher to develop a regression equation which will adequately take into account these two factors and which can be readily used by industry to attain optimal pushing conditions. By establishing optimal energy expenditure and reduced biomechanical loading, pushing performance is made more efficient and effective, and ultimately safer.

To date, worldwide, limited research has investigated the impact of load/frequency combinations on biomechanical forces exerted in the initial, sustained and ending stages of the task, or the energy cost of performing the task. This research will therefore be ground-breaking in establishing basic standards and guidelines relative to dynamic pushing tasks in industry.

It is critically important that you be free of any injuries and illnesses at the time of testing, as these may reduce the validity of your results. Please be open and honest regarding any injuries or illnesses prior to the commencement of testing. Prior to any data collection, all procedures will be thoroughly explained to you, and you will be free to ask questions at any stage. Once you have signed the required informed consent, acknowledging your willingness to participate in the study, you will be given the opportunity to habituate yourself to the testing procedures.

You will be required to come to the Human Kinetics and Ergonomics Department at Rhodes University on four occasions. The first session will be a briefing session during which time the testing protocol will be explained, anthropometric and demographic data will be taken and you will be allowed to familiarise yourself with the testing procedures. The next sessions will involve actual data collection.

Data collection will involve performing the required task for a period of six minutes, over nine conditions (three per session). You will be wearing a face mask attached telemetrically to the $K4b^2$ gas analysis machine. This will enable us to analyse the air you breathe in and out, to determine how much energy you are expending. You will also be fitted with a heart rate monitor strap around your chest, which will allow us to monitor your heart rate on a regular basis. Whilst performing the task, you will be exerting forces against a Chatillon hand-held dynamometer, which will provide feedback of the forces necessary in the initial, sustained and ending stages of each push.

Perceptual feedback will be collected at various stages using a variety of psychophysical scales. These scales will be explained to you in detail.

Following the completion of all the data collection, I will gladly discuss your test results with you if you are interested, as no feedback will be given during testing. This serves to standardise data collection.

Thank you for showing interest and participating in this research. Please do not hesitate to contact me should you have any further questions.

Yours sincerely,

Adam Cripwell
(Human Kinetics and Ergonomics Masters Student)

SUBJECT INFORMED CONSENT

Department of Human Kinetics and Ergonomics

SUBJECT CONSENT FORM

I, __________________________, have been fully informed of the research entitled:

THE IMPACT OF LOAD AND FREQUENCY ON THE BIOMECHANICAL, PHYSIOLOGICAL AND PERCEPTUAL RESPONSES TO DYNAMIC PUSHING.

(Adam M. Cripwell)

and do hereby give my consent to act as a subject in the above named research.

I am fully aware of the procedures involved as well as the potential risks and benefits attendant to my participation as explained to me verbally and in writing. In agreeing to participate in this research, I waive any legal recourse against the researchers or Rhodes University, from any and all claims resulting from personal injuries sustained.

This waiver shall be binding upon my heirs and personal representatives. I realise that it is necessary for me to promptly report to the researchers any signs or symptoms indicating any abnormality or distress. I am aware that I may withdraw my consent and may withdraw from participation in the research at any time. I am aware that my anonymity will be protected at all times, and agree that the information collected may be used and published for statistical or scientific purposes.

I have read the information sheet accompanying this form and understand it. Any questions which may have occurred to me have been answered to my satisfaction.

Printed name of Subject	Signed	Date
Printed name of informed consent Administrator	Signed	Date
Printed name of Witness	Signed	Date

APPENDIX B: DATA COLLECTION

- K4b^2 Preparation
- RPE Scale
- Instructions to Subject for RPE
- Body Discomfort Map
- Instructions to Subject for Body Discomfort
- Body Contribution Map
- Instructions to Subject for Body Contribution
- Subjects Demographic and Anthropometric Data Sheet
- Randomisation of Subjects
- Data Collection Check Sheet
- Perceptual Data Collection Sheet

K4b^2 PREPARATION AND CALIBRATION CHECK LIST

- K4b^2 is set up and turned on 45 minutes before calibration to allow sufficient time to warm up.

Calibration procedure:

1. Control panel check, ensures that all computer and K4b^2 connections are functioning.
2. Room air calibration check.
3. Delay calibration check.
4. Gas calibration check.
5. Three litre turbine calibration check.

Final preparation, with subject:

1. Fit and adjust harness to the subject.
2. Fit and adjust face mask to the subject; ensure mask is secure.
3. Fit and adjust heart rate strap around subject's chest.
4. Remove K4b^2 from electrical power source and connect to batteries.
5. Fit battery pack and unit to harness.
6. Secure any loose cabling with masking tape.
7. Run final air calibration before fitting unit to face mask.
8. Allow subject to rest and monitor responses.

RPE SCALE

6.
7. VERY, VERY LIGHT
8.
9. VERY LIGHT
10.
11. FAIRLY LIGHT
12.
13. SOMEWHAT HARD
14.
15. HARD
16.
17. VERY HARD
18.
19. VERY, VERY HARD
20.

Borg's (1971) Rating of Perceived Exertion (RPE) Scale

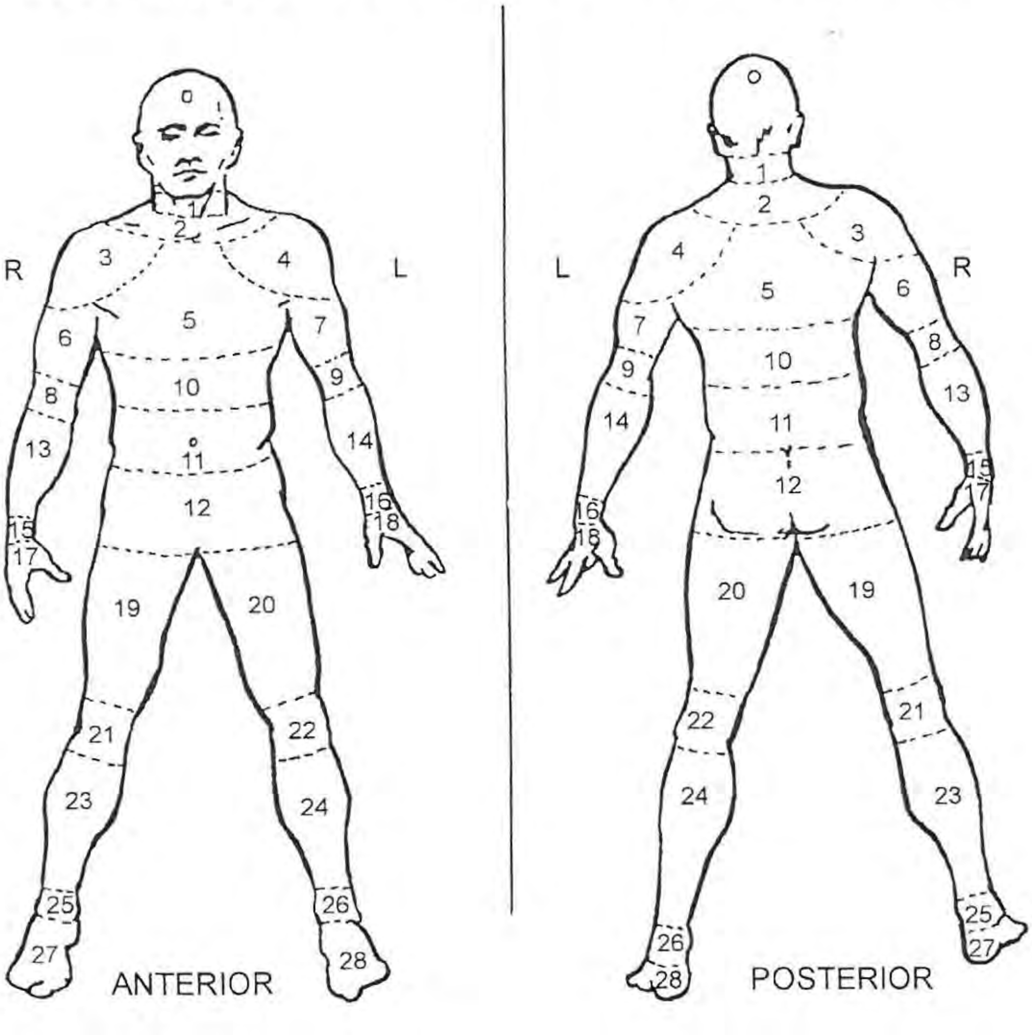
INSTRUCTIONS TO SUBJECT FOR RPE

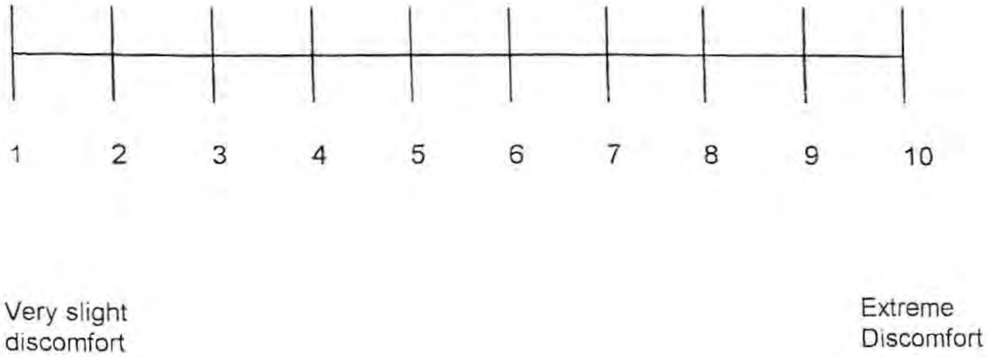
You will be required to complete nine different load/frequency pushing combinations in this study. Each combination will involve continuous pushing for six minutes while we measure various biomechanical and physiological responses. During these tests we also want you to estimate how hard you feel you are working, that is, we want you to rate the degree of perceived exertion you feel. You will be asked to point to a number on the scale presented which corresponds to your rating of perceived exertion. The first time we ask, we will be looking for a localised response, that is, how you perceive the muscles in the upper extremity are feeling. The second rating involves sensations or feelings from the central cardiorespiratory system. The scale is graded from a rating of 6 up to a rating of 20, and should closely correspond with your heart rate at that time through a factor of ten. A rating of 6 corresponds with feelings equivalent to standing quietly, while 20 reflects absolute maximal exertion. When asked to rate your work, point to the numerical value which indicates firstly your evaluation of local exertion, and secondly, point to a numerical value indicative of your cardiorespiratory strain. It is critically important that you resist the temptation to verbalise your responses, as this will negatively impact on the results, and may be difficult whilst wearing the face mask.

Try to estimate honestly and as objectively as possible. Do not underestimate the degree of exertion you experience, but do not overestimate it either. Try and be as accurate as possible. You will be requested to give ratings of perceived exertion three times during each of the nine conditions, at minutes 2, 4 and minute 6.

Corlett and Bishop's (1976) Body Discomfort Scale

BODY DISCOMFORT MAP AND RATING SCALE



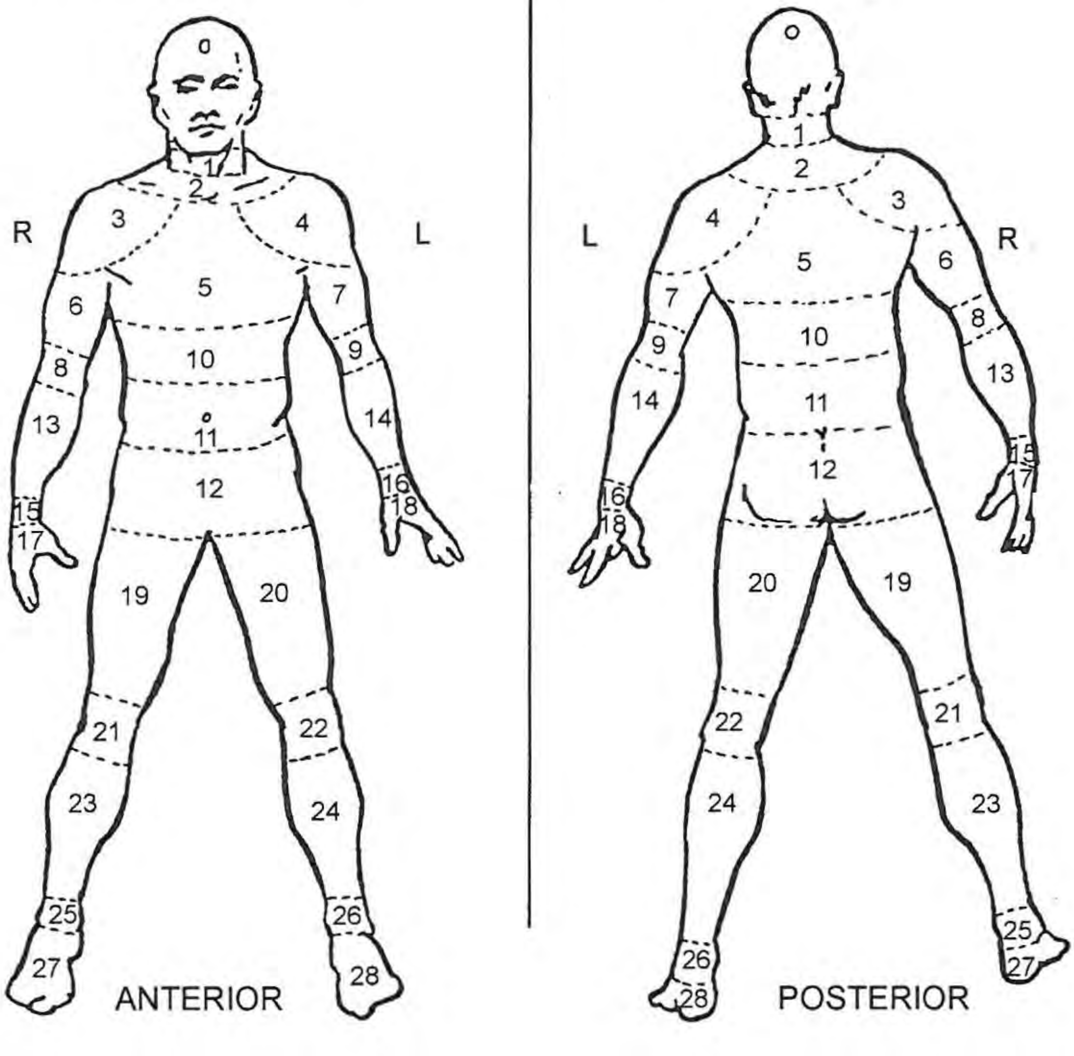


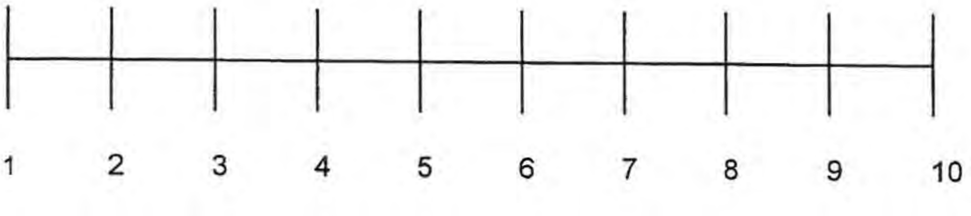
INSTRUCTIONS TO SUBJECT FOR BODY DISCOMFORT

We want you to try and determine the exact location of discomfort experienced while performing the pushing tasks. You will be required to point to the site(s) of body discomfort on the body map presented, which has been divided into anterior and posterior segments and numbered from 0-27. You will also be asked to rate the intensity of discomfort at each identified site on a ten (10) point scale, where one (1) refers to "very comfortable work" and ten (10) refers to "extreme discomfort".

Try to estimate as honestly and as objectively as possible. Do not underestimate the degree of discomfort that you feel, but also, do not overestimate it. Try to be as accurate as possible. You will be requested to identify site(s) of discomfort at the end of each condition. When you are asked to rate your discomfort, you should do so by pointing to the numerical value which corresponds to the area of discomfort, and then rate the intensity of discomfort. Once again it is critically important that you resist the temptation to verbalise your responses, as this will negatively impact on the results, and it may be difficult for us to understand whilst you are wearing the face mask.

BODY CONTRIBUTION MAP AND RATING SCALE





Adapted from: Corlett EN and Bishop RP (1976). A technique for assessing postural discomfort. **Ergonomics,** 19 (2): 175 – 182.

INSTRUCTIONS TO SUBJECT FOR BODY CONTRIBUTION

The body contribution map appears identical to the body discomfort map, but is used to gather different responses. We want you to try and determine whereabouts the body has generated the effort in order for the push effort to occur. You will be required to point to the site(s) of contribution on the body map presented, which has been divided into segments and numbered from 0-27. You will also be asked to rate the intensity of contribution at each identified site on a ten (10) point scale, where one (1) refers to "very little contribution" and ten (10) refers to "maximal contribution".

Try to estimate as honestly and as objectively as possible. Do not underestimate the degree of contribution that you experience, but also, do not overestimate it. Try to be as accurate as possible. You will be requested to identify site(s) of contribution at the end of each condition. When you are asked to rate your contribution, you should do so by pointing to the numerical value which corresponds to the area of contribution, and then rate the intensity of contribution. Again it is critically important that you resist the temptation to verbalise your responses, as this will negatively impact on the results, and it may be difficult for us to understand whilst you are wearing the face mask.

SUBJECT DEMOGRAPHIC AND ANTHROPOMETRIC DATA SHEET:

Department of Human Kinetics and Ergonomics

THE IMPACT OF LOAD AND FREQUENCY ON THE BIOMECHANICAL, PHYSIOLOGICAL AND PERCEPTUAL RESPONSES TO DYNAMIC PUSHING

(Adam M Cripwell)

Name: (for record purposes only)	
Code:	G ;
Date of Birth:	
Age:	
Body Mass (kg)	
Stature (mm)	
Shoulder Height (mm)	950mm + =
Elbow Height (mm)	950mm + =
Face mask size	

Randomisation of subjects

Conditions tested during experiment:

	Load		
Frequency	**225kg**	**350kg**	**500kg**
1 push/ 20sec	1	2	3
1 push/ 40 sec	4	5	6
1 push/ min	7	8	9

The 30 subjects were divided into groups of two. Each pairing performed nine conditions in total, divided into three experimentation sessions of three conditions each.

Group	Random Sequence
G1	159 483 726
G2	591 834 267
G3	915 348 672
G4	159 483 726
G5	591 834 267
G6	267 591 834
G7	672 915 348
G8	726 159 483
G9	267 591 834
G10	672 915 348
G11	348 672 915
G12	483 726 159
G13	834 267 591
G14	348 672 915
G15	483 726 159
G16	834 267 591

DATA COLLECTION AND CHECK SHEET

Date: ____________________

Code: G ;

Condition sequence: ______________________

Condition Performed: ______________________

TIME

VARIABLE/ CHECK	Min 0 - 1	Min 1 - 2	Min 2 - 3	Min 3 - 4	Min 4 - 5	Min 5 - 6
Speed (tick)						
Push forces (tick)	■		▨		▨	
K4b^2 mark (tick)	■	■	■		■	
Central RPE	■	■	■		■	
Local RPE	■	■	■		■	
Digital Video (tick)	■	■		■		■

Comments: ____

____

____

____

Body Discomfort

Site	Rating

Body Contribution

Site	Rating

PERCEPTUAL RESPONSES

Date: ______________________________

Code: ______________________________

Random Sequence: ______________________________

Condition: ____________________

	Min 3 - 4	Min 5 - 6
Central RPE		
Local RPE		

Body Discomfort

Site	**Rating**

Comments: ________________________

____

____

____

Body Contribution

Site	**Rating**

Condition: ____________________

	Min 3 - 4	Min 5 - 6
Central RPE		
Local RPE		

Body Discomfort

Site	**Rating**

Comments: ________________________

____

____

____

Body Contribution

Site	**Rating**

Condition: ____________________

	Min 3 - 4	Min 5 - 6
Central RPE		
Local RPE		

Body Discomfort

Site	**Rating**

Comments: ________________________

____

____

Body Contribution

Site	**Rating**

APPENDIX C: SUMMARY REPORTS

ANOVA TABLES:

- Exerted Forces
- Stride length
- Cadence
- Heart Rate Responses
- Oxygen Consumption
- Energy Expenditure
- RPE

ANOVA TABLES

Biomechanical Measures:

Exerted Forces

Tukey HSD test; variable 'Exerted Force' Approximate Probabilities for Post Hoc Tests Error: Between MS = 1764.3, df = 261.00

cond	{1}	{2}	{3}	{4}	{5}	{6}	{7}	{8}	{9}
	212.77	**49.999**	**137.83**	**293.71**	**89.153**	**202.21**	**366.28**	**125.60**	**246.44**
1		0.000010	0.000010	0.000010	0.000010	**0.988240**	0.000010	0.000010	0.049684
2	0.00001		0.000010	0.000010	0.009310	0.000010	0.000010	0.000010	0.000010
3	0.00001	0.000010		0.000010	0.000274	0.000010	0.000010	**0.970228**	0.000010
4	0.00001	0.000010	0.000010		0.000010	0.000010	0.000010	0.000010	0.000468
5	0.00001	0.009310	0.000274	0.000010		0.000010	0.000010	0.022137	0.000010
6	**0.98824**	0.000010	0.000010	0.000010	0.000010		0.000010	0.000010	0.001516
7	0.00001	0.000010	0.000010	0.000010	0.000010	0.000010		0.000010	0.000010
8	0.00001	0.000010	**0.970228**	0.000010	0.022137	0.000010	0.000010		0.000010
9	0.04968	0.000010	0.000010	0.000468	0.000010	0.001516	0.000010	0.000010	

Stride Length

Tukey HSD test; variable 'Stride Length' Approximate Probabilities for Post Hoc Tests Error: Between MS = .00789, df = 261.00

cond	{1}	{2}	{3}	{4}	{5}	{6}	{7}	{8}	{9}
	1.3317	**1.3603**	**1.3727**	**1.3010**	**1.3180**	**1.3270**	**1.3133**	**1.3327**	**1.3140**
1		0.94527	0.690697	0.920348	0.999633	1.000000	0.996920	1.000000	0.997626
2	0.94527		0.999830	0.192014	0.651459	0.876875	0.508770	0.955431	0.529227
3	0.69069	0.99983		**0.046726**	0.293043	0.549746	0.192014	0.719179	0.204768
4	0.92034	0.19201	**0.046726**		0.998194	0.969236	0.999830	0.905444	0.999747
5	0.99963	0.65145	0.293043	0.998194		0.999985	1.000000	0.999381	1.000000
6	1.00000	0.87687	0.549746	0.969236	0.999985		0.999633	1.000000	0.999747
7	0.99692	0.50877	0.192014	0.999830	1.000000	0.999633		0.995544	1.000000
8	1.00000	0.95543	0.719179	0.905444	0.999381	1.000000	0.995544		0.996506
9	0.99762	0.52922	0.204768	0.999747	1.000000	0.999747	1.000000	0.996506	

Cadence

Tukey HSD test; variable 'cadence' Approximate Probabilities for Post Hoc Tests Error: Between MS = 39.688, df = 260.00

cond	{1}	{2}	{3}	{4}	{5}	{6}	{7}	{8}	{9}
	109.92	**108.59**	**111.87**	**109.10**	**105.02**	**105.16**	**106.78**	**103.91**	**104.97**
1		0.996452	0.956999	0.999902	0.070708	0.082503	0.593881	**0.006875**	0.059746
2	0.996452		0.533135	0.999997	0.423224	0.465799	0.972522	0.094210	0.388855
3	0.956999	0.533135		0.747535	**0.001031**	**0.001245**	**0.046339**	**0.000044**	**0.000771**
4	0.999902	0.999997	0.747535		0.238500	0.269409	0.887183	**0.037931**	0.212292
5	0.070708	0.423224	**0.001031**	0.238500		1.000000	0.978445	0.999036	1.000000
6	0.082503	0.465799	**0.001245**	0.269409	1.000000		0.986184	0.997708	1.000000
7	0.593881	0.972522	**0.046339**	0.887183	0.978445	0.986184		0.705862	0.972522
8	**0.006875**	0.094210	**0.000044**	**0.037931**	0.999036	0.997708	0.705862		0.999288
9	0.059746	0.388855	**0.000771**	0.212292	1.000000	1.000000	0.972522	0.999288	

Physiological Measures:

Heart Rate

Tukey HSD test; variable 'Heart Rate' Approximate Probabilities for Post Hoc Tests Error: Between MS = 156.90, df = 261.00

Cond	{1}	{2}	{3}	{4}	{5}	{6}	{7}	{8}	{9}
	101.18	**114.03**	**131.51**	**90.270**	**94.765**	**100.74**	**81.430**	**87.659**	**92.859**
1		0.00232	0.000010	0.021261	0.555373	1.000000	0.000010	0.000991	0.198310
2	0.00232		0.000012	0.000010	0.000010	0.001331	0.000010	0.000010	0.000010
3	0.00001	0.00001		0.000010	0.000010	0.000010	0.000010	0.000010	0.000010
4	0.02126	0.00001	0.000010		0.902006	0.033063	0.136156	0.996701	0.996881
5	0.55537	0.00001	0.000010	0.902006		0.650671	0.001255	0.407423	0.999662
6	1.00000	0.00133	0.000010	0.033063	0.650671		0.000010	0.001741	0.264260
7	0.00001	0.00001	0.000010	0.136156	0.001255	0.000010		0.595444	0.012242
8	0.00099	0.00001	0.000010	0.996701	0.407423	0.001741	0.595444		0.800905
9	0.19831	0.00001	0.000010	0.996881	0.999662	0.264260	0.012242	0.800905	

Oxygen Consumption

Tukey HSD test; variable '$\dot{V}O_2$' Approximate Probabilities for Post Hoc Tests Error: Between MS = 6.7540, df = 261.00

cond	{1}	{2}	{3}	{4}	{5}	{6}	{7}	{8}	{9}
	16.707	**21.680**	**26.063**	**11.155**	**13.851**	**17.024**	**9.6714**	**11.207**	**13.643**
1		0.00001	0.000010	0.000010	0.000721	0.999936	0.000010	0.000010	0.000202
2	0.00001		0.000010	0.000010	0.000010	0.000010	0.000010	0.000010	0.000010
3	0.00001	0.00001		0.000010	0.000010	0.000010	0.000010	0.000010	0.000010
4	0.00001	0.00001	0.000010		0.001935	0.000010	0.398534	1.000000	0.006477
5	0.00072	0.00001	0.000010	0.001935		0.000112	0.000010	0.002643	0.999998
6	0.99993	0.00001	0.000010	0.000010	0.000112		0.000010	0.000010	0.000026
7	0.00001	0.00001	0.000010	0.398534	0.000010	0.000010		0.349248	0.000010
8	0.00001	0.00001	0.000010	1.000000	0.002643	0.000010	0.349248		0.008622
9	0.00020	0.00001	0.000010	0.006477	0.999998	0.000026	0.000010	0.008622	

Energy Expenditure

Tukey HSD test; variable 'Energy Expenditure' Approximate Probabilities for Post Hoc Tests Error: Between MS = .74233, df = 261.00

cond	{1}	{2}	{3}	{4}	{5}	{6}	{7}	{8}	{9}
	6.2902	**8.1400**	**9.8493**	**4.1979**	**5.2135**	**6.3923**	**3.6442**	**4.2199**	**5.1306**
1		0.000010	0.000010	0.000010	0.000054	0.999949	0.000010	0.000010	0.000016
2	0.000010		0.000010	0.000010	0.000010	0.000010	0.000010	0.000010	0.000010
3	0.000010	0.000010		0.000010	0.000010	0.000010	0.000010	0.000010	0.000010
4	0.000010	0.000010	0.000010		0.000201	0.000010	0.237198	1.000000	0.000940
5	0.000054	0.000010	0.000010	0.000201		0.000014	0.000010	0.000299	0.999990
6	0.999949	0.000010	0.000010	0.000010	0.000014		0.000010	0.000010	0.000011
7	0.000010	0.000010	0.000010	0.237198	0.000010	0.000010		0.191590	0.000010
8	0.000010	0.000010	0.000010	1.000000	0.000299	0.000010	0.191590		0.001418
9	0.000016	0.000010	0.000010	0.000940	0.999990	0.000011	0.000010	0.001418	

Central RPE

Tukey HSD test; variable crpe (Spreadsheet20) Approximate Probabilities for Post Hoc Tests Error: Between MS = 2.9526, df = 261.00

cond	{1}	{2}	{3}	{4}	{5}	{6}	{7}	{8}	{9}
	10.467	**11.667**	**13.500**	**9.6000**	**11.000**	**11.767**	**8.6333**	**10.000**	**10.533**
1		0.145948	0.000010	0.576218	0.956303	0.081652	0.001209	0.980655	1.000000
2	0.145948		0.001209	0.000142	0.854786	1.000000	0.000010	0.005409	0.206196
3	0.000010	0.001209		0.000010	0.000011	0.003021	0.000010	0.000010	0.000010
4	0.576218	0.000142	0.000010		0.042525	0.000045	0.419567	0.992946	0.470667
5	0.956303	0.854786	0.000011	0.042525		0.729278	0.000013	0.370607	0.980655
6	0.081652	1.000000	0.003021	0.000045	0.729278		0.000010	0.002237	0.121247
7	0.001209	0.000010	0.000010	0.419567	0.000013	0.000010		0.053274	0.000645
8	0.980655	0.005409	0.000010	0.992946	0.370607	0.002237	0.053274		0.956303
9	1.000000	0.206196	0.000010	0.470667	0.980655	0.121247	0.000645	0.956303	

Local RPE

Tukey HSD test; variable lrpe (Spreadsheet20) Approximate Probabilities for Post Hoc Tests Error: Between MS = 3.2258, df = 261.00

cond	{1}	{2}	{3}	{4}	{5}	{6}	{7}	{8}	{9}
	9.2667	**10.900**	**12.967**	**8.8333**	**10.233**	**11.267**	**8.1667**	**9.7333**	**10.367**
1		0.012763	0.000010	0.991033	0.483960	0.000568	0.299394	0.985421	0.299394
2	0.012763		0.000312	0.000312	0.883408	0.997144	0.000010	0.224127	0.966411
3	0.000010	0.000312		0.000010	0.000010	0.007595	0.000010	0.000010	0.000011
4	0.991033	0.000312	0.000010		0.063674	0.000015	0.883408	0.585148	0.026447
5	0.483960	0.883408	0.000010	0.063674		0.387053	0.000312	0.977399	0.999999
6	0.000568	0.997144	0.007595	0.000015	0.387053		0.000010	0.026447	0.585148
7	0.299394	0.000010	0.000010	0.883408	0.000312	0.000010		0.020877	0.000106
8	0.985421	0.224127	0.000010	0.585148	0.977399	0.026447	0.020877		0.910701
9	0.299394	0.966411	0.000011	0.026447	0.999999	0.585148	0.000106	0.910701	

APPENDIX D: PAPERS PUBLISHED DURING THIS RESEARCH

Cripwell A, Cowen K and Skelton S (2006). Static vs.Dynamic maximal pushing at two common handle heights. **Proceedings of Ergonomic Society of South Africa Conference.** Johannesburg, 19-20 January 2006.

James JP, Cripwell AM and Furney SE (2005). Pushing vs. Pulling strength: effect of handle height and practical ergonomics applications. **Proceedings of CybErg 2005. The Fourth International Cyberspace Conference on Ergonomics.** 15 September – 15 October.