THE EFFECT OF LOAD AND TECHNIQUE ON BIOMECHANICAL AND PSYCHOPHYSICAL RESPONSES TO LEVEL DYNAMIC PUSHING AND PULLING

BY

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ABSTRACT

Pushing and pulling research has yet to fully elucidate the demands placed on manual workers despite established epidemiological links to musculoskeletal disorders. The current study therefore aimed to quantify biomechanical and perceptual responses of male operators to dynamic pushing and pulling tasks. Three common push/pull techniques (pushing, one handed and two handed pulling) were performed at loads of 250kg and 500kg using an industrial pallet jack in a laboratory environment. Thirty six healthy male subjects (age: 21 ±2 years, stature: 1791 ±43 mm and body mass: 77 ±10 kg) were required to perform six loaded experimental and two unloaded control conditions. Hand force exertion, muscle activity and gait pattern responses were collected during 10m push/pull trials on a coefficient controlled walkway; body discomfort was assessed on completion of the condition.

Horizontal hand force responses were significantly ($p<0.05$) affected by load, with a linear relationship existing between the two. This relationship is determined by specific environmental and trolley factors and is context specific, depending on factors such as trolley maintenance and type of flooring. Hand force exertion responses were tenuously affected by technique at higher loads in the initial and sustained phases, with pushing inducing the greatest hand forces. Comparison of the motion phases revealed significant differences between all three phases, with the initial phase evidencing the greatest hand forces. Muscle activity responses demonstrated that unloaded backward walking evoked significantly higher muscle activation than did unloaded forward walking whilst increased muscular activity during load movement compared to unloaded walking was observed. However increasing load from 250kg to 500kg did not significantly impact the majority of muscle activity responses. When considering technique effects on muscle activity, of the significant differences found, all indicated that pushing imposed the least demand on the musculoskeletal system. Gait pattern responses were not significantly affected by load/technique combinations and were similar to those elicited during normal, unloaded walking.

Perceptually, increased load led to increased perception of discomfort while pushing resulted in the least discomfort at both loads. From these psychophysical responses, the calves, shoulders and biceps were identified as areas of potential musculoskeletal injury, particularly during one and two handed pulling.

Pushing elicited the highest hand forces and the lowest muscle activity responses in the majority of the conditions whilst psychophysical responses identified this technique as most satisfactory. Current results advocate the use of pushing when moving a load using a wheeled device. Suitability of one and two handed pulling remains contradictory, however results suggest that one handed pulling be employed at lower loads and two handed pulling at higher loads.

DEDICATION

In appreciation for her constant love, support, confidence and inspiration I would like to dedicate this thesis to the memory of my mother, Janet Roy Bennett.

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CHAPTER I

INTRODUCTION

BACKGROUND TO THE STUDY

Traditionally the main focus of manual materials handling (MMH) research has been on lifting, and associated holding, carrying and lowering, these being not only the most common, but also the most physically demanding and hazardous forms of MMH. Due to the oft cited relationship between lower back pain and lifting, it has been acknowledged that lifting is neither biomechanically nor physiologically the preferable form of load movement (Resnick and Chaffin, 1995). Consequently, attempts have been made to eradicate the lifting component of tasks, an action which has seen a concurrent rise in the use of manual handling devices (MHDs), introducing a pushing/pulling element (`Hoozemans **et al.**, 1998). While there has been interest in pushing/pulling for over thirty years (Martin and Chaffin, 1972; Datta **et al.**, 1978; Warwick **et al.**, 1980; Hoozemans **et al.**, 1998; Li **et al.**, 2008), a deficit of knowledge regarding the musculoskeletal, physiological and psychophysical strain experienced by workers during pushing/pulling remains (van der Beek **et al.**, 1999; Hoozemans **et al.**, 2004). Several studies have identified epidemiological links between musculoskeletal disorders (MSDs) and pushing/pulling (Lee **et al.**, 1991; van der Beek **et al.**, 1999; Hoozemans **et al.**, 2004), yet the causative factors involved remain unclear and may only be elucidated through further research.

While early pushing/pulling studies focussed predominantly on static tasks (Ayoub and McDaniel, 1974; Kroemer, 1974; Chaffin **et al.**, 1983), it has become increasingly apparent that these activities are rarely entirely static; rather there is a dominance of dynamic actions when considering the walking element (Lee **et al.**, 1991). Thus although dynamic push/pull tasks maintain static components in the upper extremities, more importance needs to be placed on the dynamic elements of the job to advance understanding of this complex situation. These dynamic aspects are indeed multifaceted and difficult to assess as they introduce a host of complicating task, environment, operator and design factors (Mack **et al.**, 1995;

Jung **et al.**, 2005). In addition to this, workers generally make use of a variety of push/pull techniques; namely forward pushing, forward pulling (one handed) and backward pulling (two handed) which necessitate a combination of forward and backward walking. Jung **et al.** (2005) suggest that the fourth option, backward pushing, is rarely evidenced in industry and thus is negligible in the context of the current study. The amalgamation of these numerous factors result in unique combinations of circumstances, such that any industrial setting may vary considerably from a seemingly similar one, thereby complicating the practical application of any research findings completed under ‘ideal’ laboratory conditions.

While authors agree that two handed pushing imposes least stress on the worker from a biomechanical perspective such as lower back load (Schibye **et al.**, 2001; de Looze **et al.**, 2000), this is not always feasible. Often visual constraints are imposed by the height of the load and thus increase the risk of slip, trip and fall accidents. Walking backwards while pulling also limits the visual field, and consequently one handed forward pulling is often utilised. This method is however difficult to employ for heavy loads (Li **et al.**, 2008). Furthermore the differences between these techniques with regard to gait patterns and muscle activity are, as yet, unknown. This highlights the need for research in this area with the intention of determining the technique most likely to optimise worker performance and decrease injury risk.

The current study chose to focus on several of the aforementioned factors, suggested by Mack **et al.** (1995) and Jung **et al.** (2005), which are important in push/pull tasks. Of particular significance are the motion phases that are evidenced during dynamic pushing/pulling. These include the initial phase where force is required to overcome inertia and commence movement, the sustained phase to maintain movement, and the ending phase which typically requires a ‘reversal’ of force exertion to bring the trolley to a stop (van der Beek **et al.**, 1999). These motion phases have been researched with reference to hand forces where it has been agreed that hand force exertion is greatest in the initial and ending phases during level exertions (Donders **et al.**, 1997; van der Beek **et al.**, 2000; Jansen **et al.**, 2002; Bennett **et al.**, 2008). Hand forces have typically been used in push/pull research to indicate the amount of stress imposed on the human operator.

In 2005 Todd identified a specific research deficiency in terms of gait pattern responses to pushing and pulling, suggesting that the sound understanding of normal gait patterns that currently exists does not extend to pushing/pulling research. While dynamic movements have been associated with the incidence of slip, trip and fall accidents (Winter, 1995; Boocock **et al.**, 2006; England and Granata, 2007), few studies have attempted to quantify or describe any changes that may occur in the gait cycle during dynamic pushing/pulling tasks. This may be partly due to the relative lack of understanding of the relationships between gait parameters (Zatsiorski **et al.**, 1994) and the additional complexity of conducting dynamic pushing/pulling research. Several studies have investigated muscle activity changes occurring during backward and forward walking in an attempt to determine which mode of walking is more physiologically taxing on workers. As yet this has not been linked to pushing/pulling where these modes of walking are integral. Backward walking has tenuously been linked to higher energy expenditure as a result of greater muscle activity (Grasso **et al.**, 1998) and the current study hypothesised that this would be exacerbated when moving an additional load.

As there is inadequate literature in the area of gait and muscle activity responses to pushing/pulling, one must draw on research pertaining to normal walking. Both backward and forward walking are applicable as pushing/pulling utilise both directions of movement. Noticeably, posture has been shown to influence gait patterns (Winter, 1995; Grasso **et al.**, 2000). As pushing/pulling often elicit extreme postures to allow use of body weight, this could theoretically impact the gait patterns. Furthermore postures vary between pushing and pulling, further complicating the assessment of this aspect of push/pull tasks (Chaffin **et al.**, 1983; Daams, 1993).

Muscle activity in the lower extremities has generally been found to vary between forward and backward walking (Thorstensson, 1986; Grasso **et al**., 1998) although some authors dispute this (Winter **et al.**, 1989). If differences in muscle activity occur between walking directions, this indicates varying demands being placed on the body and these would be further exacerbated by posture changes, such as increased forward and backward leaning, evidenced during pushing/pulling. Furthermore, examining the levels of muscular activity during ‘normal’ walking and push/pull conditions allows for the quantification of additional muscular cost placed on the body during the movement of a load. Muscle activity plays a key role in clarifying the demands placed on the musculoskeletal system and may help to identify the possibility of fatigue and risk of overexertion. The relationship, if any such exists, between hand force, gait pattern and muscle activity responses has yet to be established and quantified; hence this focus is a key concern of the current study.

A range of push/pull research has indicated a linear relationship between load and force requirement (Resnick and Chaffin, 1995; van der Beek **et al.,** 2000; Haslam **et al.**, 2002; Cripwell, 2007; Bennett **et al.**, 2008) and thus it appears that load is an easily manipulated task factor with a well defined relationship with task demands. Load manipulation was chosen in the current study in order to alter the demands of the experimental conditions to ascertain responses to varying push/pull task demands.

This research undertook to investigate the hand force exertion, gait pattern and muscle activity responses that may occur during a variety of dynamic pushing and pulling conditions. Load and push/pull technique were manipulated to produce varying task demand combinations which are expected to impact on hand forces, muscle activity and gait pattern responses during the movement. It was the aim to quantify these changes with the purpose of furthering the understanding of the physical and psychophysical stresses imposed on the worker during dynamic pushing/pulling tasks.

STATEMENT OF THE PROBLEM

In order to fully comprehend the risk of injury and fatigue associated with pushing and pulling, it is necessary to consider biomechanical and perceptual responses to these tasks. A variety of studies in this field have investigated hand force exertion with particular concern toward the three motion phases, however these hand forces have seldom been connected to other biomechanical or perceptual measures and have typically been considered in isolation. As yet little is known about lower limb muscle activity responses to dynamic pushing, one handed and two handed pulling. Furthermore the gait pattern responses under these conditions are under researched, particularly considering the forward and backward walking components involved. Moreover, further changes in load have been associated with changes in required hand force exertion, and this is likely to affect both muscle activity and gait pattern responses. Perceptual responses to pushing/pulling provide a subjective impression of the task, however this may provide key information in determining potential musculoskeletal risk. Thus the current study aimed to investigate responses to three common push/pull techniques under varying task demands with the intention of determining the technique most likely to lead to work optimisation and minimisation of injury risk.

In order to determine if these differences exist, a total of six experimental conditions, consisting of three techniques used to move two loads, were used. To provide a baseline comparison for muscle activity and gait pattern responses, two control conditions were also performed, normal unloaded forward and backward walking.

RESEARCH HYPOTHESIS

The objective of the current research was to examine biomechanical and psychophysical responses to changes in technique and load during dynamic pushing and pulling activities. Changing task demands are expected to impact both biomechanical and perceptual responses. The biomechanical aspects are represented by investigation of hand force exertion, lower limb muscle activity and gait pattern responses. The body discomfort scale reflects perceptual responses.

It is expected that hand forces will be lowest for pushing as compared to either one or two handed pulling. Consequently it is expected that muscle activity and perceptual responses will also be lowest during these conditions. The initial phase is expected to elicit the highest magnitude of hand forces; furthermore peak ending forces are likely to be higher than sustained forces. It is further expected that the asymmetrical nature of one handed pulling will place dissimilar demands on the musculoskeletal system when compared to two handed pulling, although muscular demands are likely to be higher in backward (two handed) rather than forward (one handed) pulling. As a result of the additional demand of moving a load, it is expected that muscle activity and gait patterns will vary significantly from normal, unloaded walking 'control' conditions. Finally it is expected that increases in load, and thus greater task demands, will increase both biomechanical demand and subjective responses.

STATISTICAL HYPOTHESES

Biomechanical hypotheses

Impact of load

Hypothesis 1 (a)(i): The biomechanical responses are equal at both 250kg and 500kg loads.

H_0: $\mu_{\text{Bio250(Push/1HPull/2HPull)}} = \mu_{\text{Bio500(Push/1HPull/2HPull)}}$

H_A: $\mu_{\text{Bio250(Push/1HPull/2HPull)}} \neq \mu_{\text{Bio500(Push/1HPull/2HPull)}}$

Where: Bio = biomechanical responses (hand forces, muscle activity and gait patterns)
Push= two handed pushing, 1HPull= one handed pulling, 2HPull= two handed pulling.

Impact of technique

Hypothesis 1 (a)(ii): The biomechanical responses are equal for all push/pull techniques.

H_0: $\mu_{\text{BioPush}} = \mu_{\text{Bio1HPull}} = \mu_{\text{Bio2HPull}}$

H_A: $\mu_{\text{BioPush}} \neq \mu_{\text{Bio1HPull}} \neq \mu_{\text{Bio2HPull}}$

Where: Bio = biomechanical responses (hand forces, muscle activity and gait patterns).

Technique refers to forward bilateral pushing, backward bilateral pulling and unilateral forward pulling

Hypothesis 1 (b): The hand forces (HF) are equal for all phases (initial, sustained, ending) for all experimental conditions.

H_0: $\mu_{HFIP} = \mu_{HFSF} = \mu_{HFEP}$

H_A: $\mu_{HFIP} \neq \mu_{HFSF} \neq \mu_{HFEP}$

IP refers to initial peak force, SF refers to sustained force and EP refers to ending peak force

Hypothesis 2 (a) (i): Forward walking responses (in muscle activity and gait patterns) are equal to pushing and one handed pulling responses.

H_0: $\mu_{Forward} = \mu_{Pushing} = \mu_{1HPull}$

H_A: $\mu_{Forward} \neq \mu_{Pushing} \neq \mu_{1HPull}$

Where: Forward = normal, unloaded forward walking
Pushing = pushing 250kg and 500kg loads
1 H Pull = unilateral forward pulling of 250kg and 500kg loads

Hypothesis 2 (a) (ii): Backward walking responses (muscle activity and gait patterns) are equal to two handed pulling responses.

H_0: $\mu_{Backward} = \mu_{2HPull}$

H_A: $\mu_{Backward} \neq \mu_{2HPull}$

Where: Backward = normal, unloaded backward walking
2 H Pull = two handed backward pulling of 250kg and 500kg

Psychophysical hypothesis

Hypothesis 3: The perceptual responses (Body discomfort, BD) are equal for all load and push/pull technique combinations.

H_0: $\mu_{BD1} = \mu_{BD2} = \ldots\ldots \mu_{BD6}$

H_A: $\mu_{BD1} \neq \mu_{BD} \neq \ldots\ldots \mu_{BD6}$

1, 2…6 represent the six experimental conditions

Technique refers to forward bilateral pushing, backward bilateral pulling and unilateral forward pulling

DELIMITATIONS

The study aimed to investigate the impact of load and push/pull technique on individuals' hand force, gait pattern, muscle activity and psychophysical responses. A sample of 36 male participants aged between 18 and 26 years, drawn from the Rhodes University student population, volunteered to participate. A stature restriction between 1700 and 1900mm was set to ensure that trolley handle height was approximately at participants' elbow height. Self report indicated that no participants had a history of musculoskeletal problems and all were free from injury. Environmental factors were controlled through the use of a laboratory. Subjects wore standardised work boots and walked at a relative speed of 0.45-0.55statures.s^{-1}. The independent variables were restricted to load and push/pull technique as these were the variables of interest.

Participants were given a letter of information outlining the aims and procedures of the study and signed informed consent before participating. Extensive habituation aimed to ensure the participants were comfortable with testing procedures and could adhere to standardised speed and technique requirements during testing. Experimentation took place in one ninety minute session, involving all six experimental conditions and two control conditions. Three successful trials were performed for each condition, with adequate rest periods. Dependant variables were delimited to exerted hand forces, gait patterns and muscle activity of the lower limb while psychophysical variables were delimited to perceptions of body discomfort.

LIMITATIONS

Although every effort was made to rigorously control as many extraneous variables as possible, several factors posed limitations to the current study and should be taken into consideration when examining the results.

The subjects who participated in the study had no previous experience in manual materials handling activities such as pushing/pulling; furthermore this was a young, healthy student population and consequently may not be an accurately representative sample of South African manual workers.

While technique was controlled rigorously, the dynamic nature of the tasks performed meant that a certain amount of variability was intrinsic in the manner in which each participant pushed/pulled.

The perceptual scale used in this study was comprehensively explained, both verbally and in printed form, to the participants. However the understanding and application of the scale remained subjective and therefore this may have been a limitation of this investigation.

CHAPTER II

REVIEW OF RELATED LITERATURE

INTRODUCTION

Hoozemans **et al.** (1998) suggested that recognition of the hazards allied to lifting have led to redesign of many manual materials handling (MMH) tasks in an attempt to reduce injury rates, and thus an increase in use of manual handling devices (MHDs) has been evidenced. This requires hoists, wheeled carts, containers and trolleys to be pushed and pulled, allowing the transfer of heavy loads with minimal risk to the operator (van der Beek **et al.**, 1999; Ciriello **et al.**, 1999a). Initially it was thought that this was the most ideal and cost effective solution and indeed Straker **et al.** (1996) reported physical limits double that of lifting for pushing and pulling. However the assumption that changing the mode of load movement automatically reduces stresses needs to be questioned. Resnick and Chaffin (1995) proposed that this in fact just changes the nature of the stress, rather than eliminating it. This view has been supported by several authors who have shown musculoskeletal stresses associated with pushing and pulling that differ from those occurring during lifting (Hoozemans **et al.**, 1998; van der Beek **et al.**, 1999). Haslegrave (2004) concurs, suggesting that the vertical forces previously associated with lifting are replaced by horizontal forces characteristic of pushing and pulling and further argues that the use of MHDs rarely removes all force exertion from a task.

Limited research is a major contributing factor to the lack of understanding that surrounds the risks associated with pushing and pulling. Several authors have advocated investigation of this field (Hoozemans **et al.**, 1998; Kuiper **et al.**, 1999; van der Beek **et al.**, 1999), yet there remains a scarcity of information regarding this. More recently there appears to be increased scientific interest in the subject, with various aspects such as handle height (Martin and Chaffin, 1972; Warwick **et al.**, 1980; Chaffin **et al.**, 1983; Daams, 1993; Lee **et al.**, 1991; Resnick and Chaffin, 1995; Okunribido and Haslegrave, 1999), load and hand forces (Resnick and Chaffin, 1995; Al-Eisawi **et al.**, 1999a; 1999b; van der Beek **et al.**, 2000), force direction (De Looze **et al.**, 2000) and gender differences (van der Beek **et al.**, 2000) being investigated in relation to pushing and pulling. Furthermore studies are beginning to focus on gathering epidemiological evidence of musculoskeletal disorders (MSDs) associated with pushing and pulling (Lee **et al.**, 1989; van der Beek **et al.**, 1999; Hoozemans **et al.**, 2004).

MANUAL MATERIALS HANDLING

MMH encompasses a wide range of activities including lifting, lowering, carrying, pushing and pulling (Snook, 1978) and has long been a focus for a diverse range of disciplines as a result of the vast economic and human cost of injuries incurred by workers involved in MMH (Mital **et al.**, 1997). In a classic study, Snook (1978) suggested that at 23%, MMH injuries were the principal source of work injuries in the United States. Despite nearly thirty years of concentrated ergonomic attention, this statistic shows no sign of noticeably decreasing, remaining the principle cause of musculoskeletal disorders (MSDs), injuries and workplace illnesses (Dempsey and Hashemi, 1999). In the South African context Scott (1999) goes so far as to suggest that these MSDs are actually on the increase and thus they continue to cause losses both in terms of human costs (injuries and loss of abilities) and costs to society (compensation costs and loss of manpower).

Pushing and pulling capabilities have been studied within a very limited scope as compared to lifting. The use of trolleys, pallet jacks and other wheeled devices allow for the movement of a larger quantity of goods at a lower risk of injury than lifting and lowering (van der Beek **et al.**, 1999). Although there is a general lack of information regarding pushing and pulling and its relationship to musculoskeletal disorders, it is generally mentioned amongst the risk factors associated with lower back pain (van der Beek **et al.**, 1999).

PUSHING AND PULLING

Introduction

The definition of pushing and pulling proposed by Hoozemans **et al.** (1998) suggests that it is the exertion of a hand force, where the resultant force is horizontal in nature. These authors continue by illustrating the difference between pushing and pulling as having hand forces away from and towards the body respectively. It is important to note that while the majority of pushing and pulling occurs in the transverse plane this is not exclusive. A study by Garg **et al.** (1988) illustrated this when investigating the pulling of a cord while starting a lawn mower engine, here the force was predominately vertical. In addition pushing and pulling occurs not only in industry, but also in daily life such as when using supermarket trolleys, prams, wheelbarrows and lawn mowers.

Static and dynamic pushing and pulling

Within pushing and pulling research there remains a dichotomy of studies concerned either solely with static or, alternatively, exclusively dynamic push/pull activities. In previous years there was a clear focus on static activities such as free standing pushing and pulling, while more recently the focus has shifted to dynamic movements (Ayoub and McDaniel, 1974; Kroemer, 1974; Lee **et al.**, 1989; Al-Eisawi **et al.**, 1999a; Haslam **et al.**, 2002). Static push/pull tasks require predominately isometric contraction of the muscles and associated research has been concerned either with the maximum isometric forces exerted by workers (Ayoub and McDaniel, 1974; Kroemer, 1974; Chaffin **et al.**, 1983) or with the forces occurring at the lower back (Lee **et al.**, 1989; Schibye **et al**., 2001). Current literature emphasises the predominance of dynamic movements within the workplace, particularly concerning the use of MHDs (Lee **et al.,** 1991) and thus the applicability of static push/pull recommendations becomes questionable within industry. Lee **et al.** (1991) demonstrate this, showing that the postures adopted during dynamic pushing/pulling differ from those during static tasks, even at the same level of exertion.

It is important to make the distinction between static pushing/pulling and static components of dynamic pushing/pulling. Although most of these tasks may be dynamic in nature, a static component remains; while the lower body is involved in walking (dynamic work), the upper body is used to control the load and the muscles are isometrically contracted (static work). This static activity has been identified as a cause of injury and as having a great influence on the cardiovascular system (Hoozemans **et al.**, 2004). This combination of static and dynamic work is important to acknowledge when assessing the demands of a push/pull task.

Movement phases/force components

Dynamic pushing/pulling has been subdivided into three acknowledged phases of movement; initial, sustained and ending. The initial phase occurs where one has to overcome inertia and accelerate the object, the sustained phase whereby the object is kept at a constant velocity, and the ending phase where the object is decelerated and brought to a stop (van der Beek **et al.**, 1999). Use of 'constant velocity' in this definition is arguably inaccurate. During the sustained phase there are fluctuations in velocity as a result of the gait cycle (see Figure 1) and hence hand forces; thus cannot truly be at a 'constant velocity'. An improved definition requires that the sustained force be that which is required to keep the object in motion. These phases can be seen in Figure 1, which shows a typical force graph from a dynamic pull trial.

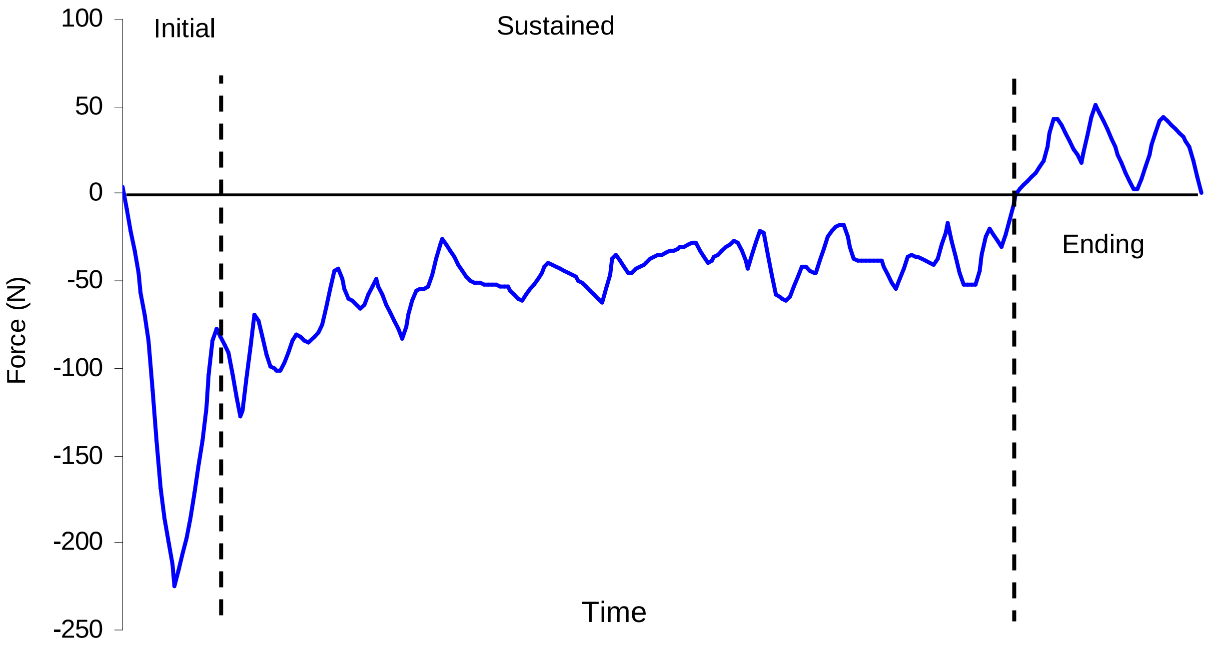


Figure 1: Illustration of forces exerted on a trolley during a dynamic pull, with motion phases specified (Taken from Bennett **et al.**, 2008).

A review of relevant literature indicates that the initial phase is most likely to place high risk of injury on workers as it is here that the highest forces are required to overcome inertia, particularly in the case of excessive loads (van der Beek **et al.**, 1999). This is supported by the findings of Jansen **et al.** (2002) and Bennett **et al.** (2008) where hand force magnitude varied significantly between the phases, with the initial phase requiring greatest hand forces during level exertions.

Ferreira **et al.** (2004) classify an additional movement component, this being the manoeuvring force. This refers to the force required to change the direction of the object during movement such as when the operator has to negotiate an obstacle. These authors indicate that the manoeuvring force may be of great concern when workers are forced to adopt awkward postures in space constrained areas and are not able to utilize their body weight to aid the movement. While the current study acknowledges this supplementary movement component as significant within workplaces, it will not be used as it adds unnecessary complexity to the current multifaceted problem. However, employers must be aware of the problems created by objects and space constraints that result in a decrease of trolley mobility.

Musculoskeletal disorders: pushing and pulling

In 1998 Dempsey suggested that the biomechanical approach to ergonomics involved the design of tasks that do not result in overexertion of the musculoskeletal system specifically. However, as Buckle and Stubbs (1989) contend, this can only be based on the scientific knowledge of physical and psychophysical limitations of the human body; knowledge that is constantly evolving with ongoing research. This also involves knowledge of specific locations of problems; hence epidemiological evidence is required to determine the effects of pushing and pulling on the musculoskeletal system. Despite a deficiency of conclusive evidence linking pushing and pulling to specific musculoskeletal disorders, the MMH component of the tasks have led to them being recognised as potentially injurious (Hoozemans **et al.**, 1998; Kuiper **et al.**, 1999; van der Beek **et al.**, 1999).

Epidemiological studies have indicated an elevated risk of development of lower back disorders (LBD) in relation to lifting, while as yet evidence related to pushing and pulling is relatively limited (Kuiper **et al.**, 1999). The problem remains that the mechanisms behind pushing and pulling related injuries remain ambiguous and as such it is nearly impossible to rectify workplace situations without this knowledge. The fact that workers are often involved in dynamic, diverse tasks in which pushing/pulling is a sub-component further complicates this, as it may be difficult to isolate the push/pull tasks as the source of injury. Marras **et al.** (1995) identified cumulative load as an important causative factor of LBP and therefore it is argued that pushing and pulling significantly contributes to the accumulation of a pool of physical stress in the trunk, resulting in lower back pain (LBP). The repetitive nature of push/pull tasks contributes to the development of cumulative stress and increased injury risk (Kumar, 1995).

Van der Beek **et al.** (1999) question the almost exclusive focus on lower back injuries that has dominated push/pull research. Recent studies have additionally linked pushing and pulling to a significantly increased incidence of shoulder pain and stiffness (Hoozemans **et al.**, 2004), possibly related to the isometric activity of muscles in these areas as the worker applies force and controls the MHD. The long-term effects of overexertion during static work need to be further investigated (Jansen **et al.**, 2002).

Pushing and pulling is also associated with working above shoulder height and twisting in addition to isometric loading of the shoulder muscles, all of which are frequently associated with shoulder complaints. However more research is necessary to determine the process whereby exposure to pushing and pulling may result in these complaints (Keyserling, 2000). Pushing and pulling have further been associated with injuries to the fingers, feet, heels and lower legs directly caused by the trolley being handled (Ferreira **et al.**, 2004). The hazards that result in these injuries are acknowledged as important but are outside the scope of the current study.

Unfortunately there is little conclusive evidence describing the aetiology of musculoskeletal disorders with reference to pushing and pulling, however more recent studies have focussed on this relationship, particularly in relation to the upper extremities, lower back and shoulders (Laursen and Schibye, 2002; Hoozemans **et al.**, 2004). In addition to these cumulative problems, acute injuries in the form of slip, trip and fall accidents also occur (Grieve, 1983), and which the current study aims to consider with concern to gait patterns.

Slip, trip and fall accidents

Push/pull tasks can result in slip, trip and fall (ST&F) accidents (Grieve, 1983). Manning **et al.** (1984) described a 13% incidence of slip accidents resulting in lower back disorders (LBD) as being related to pushing and pulling. More recently Kim and Nagata (2007) suggest that ST&F are a leading cause of serious workplace injury, while Chang (2002) indicates that this is a worldwide occurrence. While the actual prevalence is not known, studies have reported between 9% and 20% of reported MMH injuries being related to pushing and pulling (Snook, 1978; Lee **et al.**, 1991).

Lipscomb **et al.** (2006) suggest that chances of ST&F are increased when manipulating large, heavy loads that obscure workers' view, a situation common in many industries. Chang (2002) separates two types of fall, those from elevation and those on the same level. Chang (2002) further indicates that while the common perception suggests that falls from elevation are more common, in fact the higher percentage of injuries derive from falls on the same level. Li **et al.** (2008) concur, adding that pushing/pulling are highly correlated with these S,T&F accidents as a result of the high shear forces between the floor and the foot. It is important to note that within ST&F research, it has not been common to consider the cases of backward walking, and Li **et al**. (2008) highlight this as a shortfall of prior research, particularly in view of backward pulling. Slip risk is historically determined on the heel strike, however during backward walking the forepart of the foot makes contact with the ground prior to the heel. Researchers must be aware of this dynamic, and investigations into backward walking are essential for further elucidation of this topic.

Factors affecting pushing and pulling

The use of MHDs in workplaces is complicated by a variety of factors, with a multifaceted interaction between these and pushing/pulling. These factors have been broadly categorised into environmental, design, task and operator factors, as seen in Figure 2.

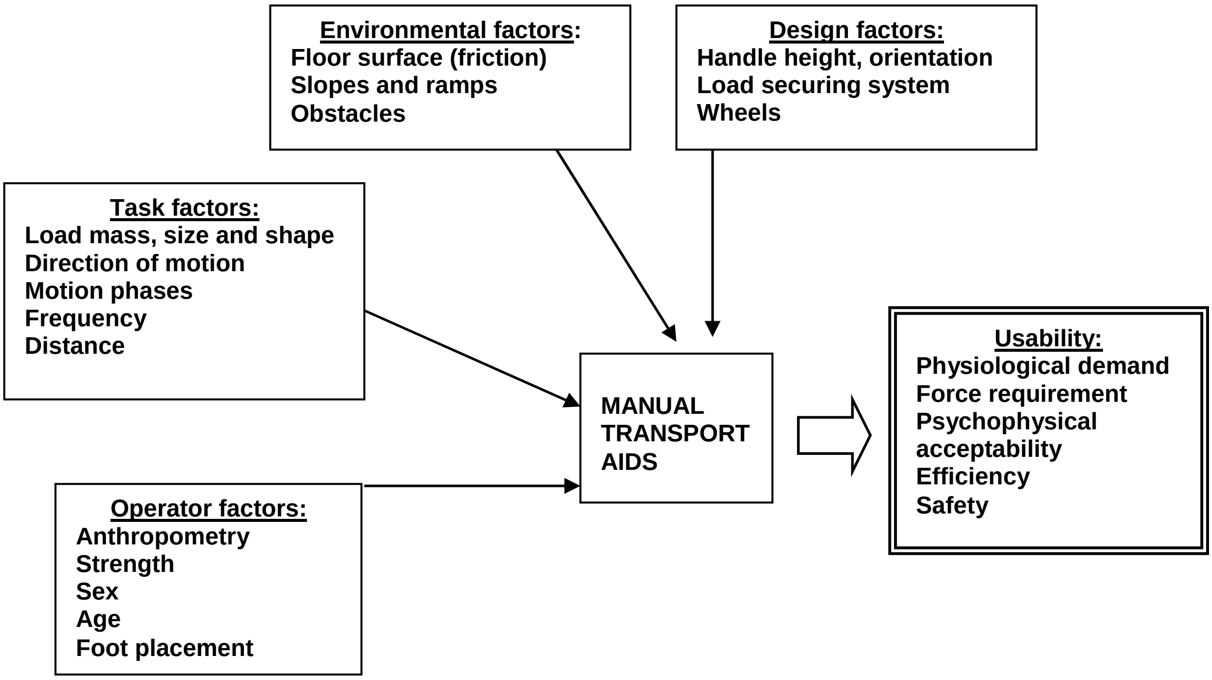


Figure 2: Factors influencing the use of a manual handling device (Adapted from Mack **et al.**, 1995; Jung **et al.**, 2005).

The majority of the factors seen in Figure 2 have been investigated in relation to pushing and pulling although, as suggested by Daams (1993), the vastly different methodologies used have hindered the comparisons drawn between them. Despite a degree of contention between researches, there are several trends that can be identified and used to make recommendations for the use of MHDs in industry. Table I details the findings and recommendations drawn from these studies.

Table I: Factors affecting pushing and pulling.

Factor, authors	Recommendations	Additional comments
Design factors		
Handle height & orientation		
Al-Eisawi **et al.** (1999 a; b)	Push: high handle height Pull : low handle height	Elbow =greatest force production
Chaffin **et al.** (1983)	Above 91 cm	
Daams (1993)	Max force at elbow height	
Kumar (1995)	100 cm	
Lee **et al.** (1991)	Push: 100cm Pull : 150cm	High handles ↑force production
Martin and Chaffin (1972)	50-90 cm ↑ push capability	
Okunribido and Haslegrave (1999)	100 cm, vertical handles	
Schibye **et al.** (2001)	Handle at shoulder height, lowest compression forces	Push = lower compressive forces than pulling
Snook and Ciriello (1991)	Push: high handles Pull: low handles	
Warwick **et al.** (1980)	Push: high handle height ↑ force Pull: low handle height ↑ force	
Wheels		
Al-Eisawi **et al.** (1999b)	All wheels orientated in direction of movement = least force requirement.	Swivelling wheels in front if pulled and in back if pushed
David and Nicholson (1985)	Larger wheels reduce intra-abdominal pressure	
Drury **et al.** (1975)	Rear when swivelling increases push speed	
Jung **et al.** (2005)	Swivelling wheels important for turning	
Environmental factors		
Floor surface, friction		
Al-Eisawi **et al.** (1999b)	Carpet required 106% higher hand forces than concrete	Hard surfaces reduce rolling friction: lower hand forces
Ciriello **et al.** (2001)	Maximum acceptable (horizontal) forces higher on high friction floors due to chance of slip	High coefficient floor: 482 kg Low coefficient floor: 332kg
Haslam **et al.** (2002)	No significant differences in maximum acceptable load between slippery and non slip flooring	
Slopes, ramps		
Winkel (1983)	↑ force requirement with ↑ slope angle	
Obstacles		
Lawson **et al.** (1993)	Ridges/curbs ↑ force requirement	
De Looze **et al.** (1995)	Lower back compression ↑ with curbs	
Task factors		
Load mass		
Datta **et al.** (1978)	↑ load mass = ↑ physiological responses	
Datta **et al.** (1983)	↑ load mass = ↑ physiological responses	
Resnick and Chaffin (1995)	Increases in load show concurrent increases in force exertion	Load limit = 225kg
Haslam **et al.** (2002)	Increases in load show concurrent increases in force exertion	
Direction of movement		
David and Nicholson (1985)	Forward bilateral push = least stress	
De Looze **et al.** (2000)	Straight, forward push = lowest stress	
Schibye **et al.** (2001)	Straight, forward push = lowest stress	
Chaffin **et al.** (1983)	Forward bilateral push = highest force production	Two handed push/pull ↑ force produced than one handed push/pull

Motion phases		
Donders **et al.** (1997)	Initial > sustained forces	Ending forces not significantly different to initial forces
Jansen **et al.** (2002)	Initial > sustained forces	
Van Der Beek **et al.** (2000)	Initial > sustained forces	
Frequency		
Snook (1978)	↑ frequency = ↓ max acceptable force	
Snook and Ciriello (1991)	↑ frequency = ↓ max acceptable force	
Speed		
Eastman Kodak (1986)	Less than 1.1 $m.sec^{-1}$ recommended	
Jansen **et al.** (2002)	↑ acceleration = ↑ initial forces	
Jung **et al.** (2005)	Slow speeds preferable	
Distance		
Snook (1978)	↑ distance = ↓ max acceptable force	
Snook and Ciriello (1991)	↑distance = ↓ max acceptable force	
Operator factors		
Anthropometry		
Ayoub and McDaniel (1974)	Higher body weight = greater push strength	
Sex		
Daams (1993)	Max force: males > females	
Fothergill **et al.** (1991)	Max force: males > females	
Kumar (1995)	Max force: males > females	
Foot placement		
Ayoub and McDaniel (1974)	Push: rear foot 10% shoulder height Pull: feet 10% of shoulder height	
Chaffin **et al.** (1983)	Feet staggered ↑ force production	

The factors outlined in Table I have been investigated in push/pull research with the aim of designing tasks that are both safe and efficient. There are several important features of the task that directly influence aspects such as posture, physiological load and technique of push/pull that are important to discuss in light of the independent variables considered in the current investigation.

Handle height

The interaction between trolley handle height and the worker's anthropometric dimensions, specifically stature, directly affect working posture and biomechanical forces experienced by workers (Chaffin **et al.**, 1983). As a result much research has centred on determining efficient handle heights for MHDs (Daams, 1993; Resnick and Chaffin, 1995; de Looze **et al.**, 2000; Hoozemans **et al.**, 2004). Chaffin **et al.** (1983) concluded that the highest forces could be generated for both pushing and pulling at low handle heights due to forward and backward leaning, thus increasing the use of body weight in the movement. High handle heights encouraged more erect postures, less turning force and lower force producing capabilities. When comparing pushing and pulling, high handle heights favoured greater force prediction when pushing, and low handle heights when pulling (Warwick **et al.**, 1980; Snook and Ciriello, 1991; Al-Eisawi **et al.**, 1999a; b). However, the majority of these studies involved static push/pulls and walking while pushing/pulling was not considered.

It is clear that both posture and strength (force production) vary with handle height (Chaffin **et al.**, 1983; Haslegrave, 2004). Low handle heights appear optimal as they allow for great force production; however these increase the compressive forces on the lumbosacral (L_5S_1) region of the spine such that the worker is exposed to increased injury risk (Schibye **et al.**, 1997). Pulling results in greater L_5/S_1 compressive forces than pushing, and higher handle heights decrease compression of the lower back (Resnick and Chaffin, 1995). Thus in terms of maintaining the integrity of the lower back Lee **et al.** (1991) encourage higher handle heights for dynamic pushing/pulling tasks. This situation illustrates some of the limitations inherent in push/pull research conducted so far, this being that static recommendations are not always appropriate for dynamic situations. While low handle heights allow for backward and forward leaning, thus high force production, this is impractical while manoeuvring a wheeled cart which offers little external support to the worker. Lee **et al.** (1991) caution that low handle heights encourage extreme postures that would result in slipping and injury during cart movement.

Ideally carts should be adjustable, allowing individuals to relatavise handle heights in relation to their personal anthropometric measurements, however this is not commonly evidenced in SA industries. If absolute heights are essential as part of the trolley design, it is suggested that the handle be at elbow height, approximately between 109 and 152 cm (Chaffin **et al.**, 1983; Lee **et al.**, 1991; Resnick and Chaffin, 1995; Al-Eisawi **et al.**, 1999a).

Load

Another key factor concerning push/pull task demands is load, one of the more easily manipulated task characteristics. Several authors have described a linear increase in force requirement with increased load (Resnick and Chaffin, 1995; van der Beek **et al.,** 2000; Haslam **et al.**, 2002; Cripwell **et al.**, 2007; Bennett **et al.**, 2008). Datta **et al.** (1978; 1983) reported increased physiological responses with increased load. Although these load effects are often taken in isolation, it must be noted that the factors seen in Figure 2 will influence the load-force requirement relationship. For example, a well maintained trolley used on a level floor will require less force to move than a badly maintained trolley on an uneven floor, regardless of load. Therefore limits established in laboratory settings should be used with caution in industry where conditions are often far from ideal. To counteract this, it is suggested that instead of setting load limits, research should focus on force requirements as it is this factor that ultimately determines the demands of the task. This would allow for the limits to be set and applied to a variety of industrial settings where the factors mentioned in Table I would vary with location. Within the related literature, Resnick and Chaffin (1995) advocate limits of 225kg whilst Snook and Ciriello (1991) suggest that push and pull limits are set at 471N and 412N respectively. Van der Beek **et al.** (2000) report on acceptable loads of up to 250kg whilst Ciriello (2004) sets this at 374kg. This lack of consensus illustrates the disparity between studies setting acceptable push/pull limits. In contrast to the various load limits discussed previously, loads of up to 1500kg are not uncommon in industry (Mack **et al.**, 1995), highlighting the disproportion between acceptable guidelines and realistic work situations.

Direction of movement

Several authors agree that forward, bilateral pushing allows for the lowest compressive forces on the lower back as well as encouraging the highest force production (Chaffin **et al.**, 1983; David and Nicholson, 1985; Schibye **et al.**, 2001; de Looze **et al.**, 2000). This technique also results in the clearest view of the walking path, however this is only the case where the load is below eye level. Unfortunately it is common in industry for the load to be stacked above eye height, thus hindering vision when pushing. As a result many cases exist where operators are required to pull trolleys and so do not benefit from the advantages of forward bilateral pushing.

Unilateral forward pulling and backward bilateral pulling are common as the worker can use their body weight to aid in initial force production, particularly in the case of backward pulling (Ayoub and McDaniel, 1974). Li **et al.** (2008) propose that the use of one or two hands during pulling is related to load such that at low loads workers tend to pull forwards with one hand; however when the load exceeds this capacity, two handed pulling prevails. It was a central premise of the current study to determine what differences in responses occurred as a result of technique change in order to recommend preferable techniques of pushing/pulling.

Flooring/friction

An additional factor affecting pushing and pulling tasks is that of the coefficient of friction between the feet and the floor (Fox, 1967; Kroemer and Robinson, 1971). Foot/floor friction has been extensively researched with relation to slip, trip and fall accidents (Grieve, 1983; Chang, 2002; Lipscomb **et al.**, 2006; Holbein-Jenny **et al.**, 2007). In unconstrained postures, the maximum friction at the foot-floor interface will be the limiting factor for force production (Hoozemans **et al.**, 1998). This coefficient of friction is influenced, not only by environmental factors such as floor surface type, but also by the direction of force. If force produced is increased on the downward vertical plane (as occurs with low handle heights), there is a subsequent decrease in the coefficient of friction and thus increased chance of slipping (Grieve, 1983; Boocock **et al.**, 2006). The concept of static coefficient of friction remains relatively controversial during dynamic movements as it is argued that this measurement is inappropriate; during walking the feet are moving at heel strike rather than stationary as assumed in static conditions (Chaffin **et al.**, 1983). Li **et al**. (2008) emphasize that lower push/pull forces are required on low friction floors, but this increases slip risk. Conversely high friction floors decrease slip risk, but increase push/pull forces and thus increase the demands on the worker. There is a need to provide flooring that optimizes the relationship between risk of S,T&F accidents and the hand force requirements.

GAIT

Of the variety of human movements that interest researchers, one of the most basic is that of walking (Zatsiorsky **et al.**, 1994). Continued interest since the inception of scientific gait research by Borelli in the late 17th century has resulted in a basis for the current scientific understanding of human walking (Sutherland, 2001). Despite this there remains a void in even the most basic definitions and relationships between the variables within the gait cycle (Zatsiorsky **et al.,** 1994). This is a result of the lack of uniformity within the terms used by different researchers and can cause a degree of confusion when comparing studies to date. Furthermore the majority of the gait research conducted thus far has had a clinical focus, investigating various forms of pathological gait (Schutte **et al.**, 2000).

In terms of ergonomics research, gait in the workplace appears to have been very superficially investigated, despite the obvious fact that it is an integral part of any work situation in which walking plays a role. This is arguably of extreme importance within MMH where loads are moved from one place to another by hand. Moreover it plays an integral role in dynamic pushing and pulling where walking is the means of propulsion behind the movement of the load. It is only with a holistic understanding of pushing and pulling, including aspects such as gait analysis and associated muscle activity patterns that the interaction between the operator and the task can be understood and optimised.

Introduction to normal gait

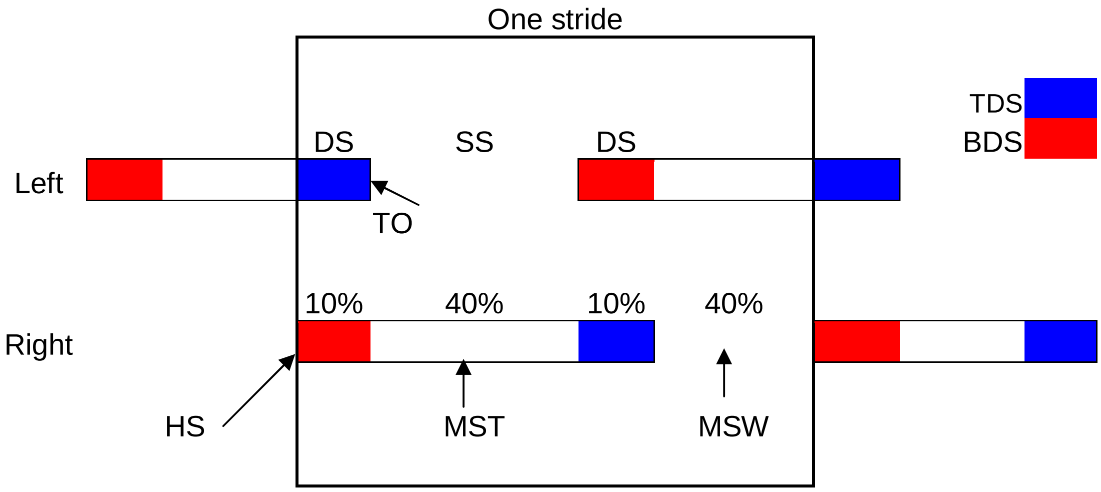
While the majority of people are aware of the term ‘gait’, it is often used interchangeably with that of ‘walking’ and occasionally ‘locomotion’. However, Whittle (1991) cautions against this loose use of terminology, suggesting that gait describes the manner of walking rather than the actual walking process. A subtle, yet important, difference in a field where there is no universally recognised system of nomenclature regarding the gait cycle (Wall **et al.**, 1987).

In 1953 Saunders **et al.** defined human locomotion as the “translation of the body from one point to another by means of a bipedal gait”. Furthermore to achieve this one must apply a force to a surface, such as the ground, which is required to resist the force, allowing the body to be driven forward. Two decades later, Whittle (1991) elucidated this further, adding that walking was characterised by use of the two legs, alternatively, providing support and propulsion. This author further separated walking gait from running by adding that walking gait displayed one foot in contact with the ground at all times.

The gait cycle: terminology and timing

The gait cycle is traditionally defined as the time between two successive occurrences of an event during the gait cycle (Whittle, 1991). It is most convenient to use the heel contact of one foot as the start of the cycle, and convention favours the heel strike of the right foot. Accordingly the current study will refer to the gait cycle in this way, with one stride being from right heel contact to subsequent right heel contact (see Figure 3).

The gait cycle was first described using observational methods, however it was the advent of photography that allowed the different phases to be scientifically identified, analysed and timed (Steindler, 1953). A basic understanding of the gait cycle is necessary in order to contextualise the current research as it is expected that the gait evidenced during pushing and pulling will differ from this ‘normal’ sequence of events. Figure 3 shows the gait cycle, displaying the terms that will be used.



Where DS = double support
SS = single support
TDS = thrusting double support
BDS= braking double support
% = amount of gait cycle typically spent in each phase
MST = mid-stride
MSW= mid-swing
HS = heel strike/contact
TO = toe off

Figure 3: The walking gait cycle (Adapted from Wall **et al.**, 1987; Whittle, 1991; Zatsiorsky **et al.**, 1994).

The stride is broadly divided into the stance phase, where the foot is in contact with the ground (heel strike-toe off), and the swing phase which lasts from toe off to the next heel contact of the same foot. The cycle is further separated into different support phases, single support (SS) and double support (DS). Single support refers to when one foot is in contact with the ground and double support when both feet are. Each gait cycle consists of two periods of double support and two periods of single support.

During the cycle, swing and support phases alternatively correspond; thus right single support corresponds with the left swing phase. The stance phases account for approximately 60% of the gait cycle and the swing phase 40% while each period of double support corresponds to 10% of the cycle (Figure 3). This pattern will vary with speed of walking as it has been shown that speed has an inverse effect on the stance phase; as speed increases so stance phases decrease. Concurrently swing phases increase and, at a point where the stance phases disappear, the individual is said to be running (Murray, 1967). When investigating foot contact patterns Wall **et al.** (1977) reported that the heel alone made initial contact and remained in contact with the ground for 57% of the total contact time. The ball of the foot made and broke contact at 20% and 80% of contact time respectively and the toe was the final contact at 35% of contact time.

Cadence, stride length and velocity

Of the gait factors commonly assessed, the two most important are cadence and stride length as these are regulated by individuals according to the situation (Whittle, 1991). Additionally they provide the simplest form of objective gait evaluation. Cadence is defined as the number of steps taken in a certain amount of time and is commonly measured in steps per minute (steps.min^{-1}) while stride length is measured in meters (m). Velocity of walking is an important parameter as changes in this generally accompany changes in cadence and stride length (Whittle, 1991). Velocity of walking is the distance covered by the body in a given time frame, measured in metres per second (m.s^{-1}). These three parameters interact such that if two are measured, the third can be calculated using variations of the following formula, depending on the quantified variables (Whittle, 1991):

$$\text{Velocity (m.s}^{-1}\text{)} = \text{stride length (m)} \times \text{cadence (steps.min}^{-1}\text{)} / 120$$

These factors interact in such a manner that they generally all alter together, thus if an individual has a slow cadence, they usually also display a short stride length and a low velocity (Whittle, 1991).

Backward and forward walking

Within pushing and pulling research with respect to gait one must acknowledge the different means of moving loads using trolleys and carts. Individuals can use one of four means, or indeed a combination throughout a work shift, namely forward pushing, forward pulling, backward pulling and backward pushing. Typically only the first three techniques are used as backward pushing is impractical due to both the structure of the musculoskeletal system and the lack of visibility during the movement. Contradictory findings in the literature have meant that, as yet, there is no definite consensus as to whether pushing or pulling is preferable, although forward pushing generally seems to be most acceptable, particularly from a biomechanical standpoint (Chaffin **et al.**, 1983; David and Nicholson, 1985; Schibye **et al.**, 2001; de Looze **et al.**, 2000). However in industry both are commonly evidenced and thus the current research needs to address both backward and forward walking as components of pushing and pulling.

Kinematics and gait characteristics

While a literature search revealed that this area of gait is not well researched, the few studies that are available reveal that two major areas of interest occur. The first, dominated by neurophysiologists, considers the neural control and organisation of muscle activity during walking (Grasso **et al.**, 1998; Lacquaniti **et al.**, 1999; Earhart **et al.**, 2001) and the second, the focus of physiologists, is the energy cost of forward and backward walking (Devita and Stribling, 1991). Grasso **et al.** (1998) refer to walking as a 'reversible' movement as it can be performed in the forward or backward direction with ease. While the first assumption that backward walking is just the reverse of forward walking may appear to be true on the surface, several authors have questioned the validity of this postulation. For example, Thorstensson (1986) noted the absence of knee flexion during the support phase while subjects walked backwards; in addition the ankle dorsiflexion seen in forward walking was not reversed to planterflexion when direction was reversed. This was supported by later research in which it was found that changes in hip angle were reversible, while changes in knee and ankle angle were not (Vilensky **et al.**, 1987; Winter **et al.**, 1989). However although there are certain kinematic differences between the movement directions, the leg has been shown to follow virtually the same movement path during backward and forward directions (Thorstensson, 1986). Li **et al.** (2008) report that different directions of walking elicit different foot contact patterns, with the heel being first point of contact during forward walking and the toe/forefoot during backward walking. This is important for the current study in that these contact patterns could identify possible problems that would result in ST&F accidents.

Thorstensson (1986) further reported decreased duration of stride times of between 8% and 14% with backward walking as compared to forward walking at the same speed. Furthermore it was shown that although the support duration was shorter while walking backwards, it remained at 62-66% of the total stride cycle time, similar to forward walking. In terms of movement trajectories, Thorstensson (1986) demonstrated almost identical movements for the two directions, occurring in opposite directions.

Muscle activity

It has been shown that walking at a constant speed on level ground results in highly reproducible intra-individual patterns of muscle activity (Inman, 1966), however it is important to note that it is common to find great inter-individual variation in muscle activity due to factors such as normalisation methods and procedures, electrode placement and muscle geometry (Lawrence and DeLuca, 1983; Yang and Winter, 1983; Goebel, 2005). Differences between forward and backward walking coordination are practically unknown (Thorstensson, 1986). The scant research that has been conducted has shown that muscle activity patterns appear to be controversial; Thorstensson (1986) noted marked differences between the gait directions while Winter **et al.** (1989) reported similarities between the two.

Masumuto **et al.** (2007) agree with Thorstensson (1986), finding that muscle activity patterns in backward walking bore little resemblance to those of forward locomotion; furthermore this suggested greater energy expenditure in backward gait. Masumoto **et al.** (2007) propose that this is due to the higher cardiopulmonary responses elicited during backward as opposed to forward walking. These authors also report increased muscle activity in the quadriceps femoris during backward walking as these muscles are required to provide the necessary propulsion. In addition, Tibialis anterior showed increased activity during backward walking due to increased dorsiflexion of the ankle (Masumoto **et al.**, 2007). Earhart **et al.** (2001) maintain that motor patterns are simply reversed for backward walking, suggesting a common general control system for locomotion. It seems that there is a common neurological pathway to control both backwards and forwards walking, however the muscle activation and kinematic responses of the anterior and posterior of the legs respond differently to a change in direction (Grasso **et al.**, 1998; Earhart **et al.**, 2001).

It is important to note these differences in muscle activity and leg kinematics as they will have a direct link to the gait patterns observed. For example, the increased dorsiflexion of the ankle seen in backward walking is thought to correspond to the reversed contact pattern (toe-heel as opposed to heel-toe) of the foot. In addition the current research is important in light of the fact that leg kinematics and muscle activity appear to vary between forward and backward walking. This would lead to differing demands, both biomechanically and physiologically, during pushing (forward walking) and pulling (backward walking) and therefore results from one might not necessarily be valid for the other.

While discrepancies between individual muscle recruitment patterns remain, there are some general muscle activation patterns during walking that have been noted in the literature (Basmajian, 1974; Perry, 1992) and these relate directly to the movements of the leg during the gait cycle. These authors inform the following discussion of muscle activity and gait timing events. It is important to note that authors such as Perry (1992) describe in extensive detail the actions and timing of all of the muscles in the lower limbs. However these have been summarised and simplified for the purposes of the current study. Figure 4 illustrates an example of raw muscle activity for the right leg during normal walking (from the current study) as recorded in real time, for four muscle groups (rectus femoris, biceps femoris, medial gastrocnemius and tibialis anterior). It demonstrates how the muscle activity relates to the basic gait cycle of one stride (heel strike right foot to subsequent heel strike right foot).

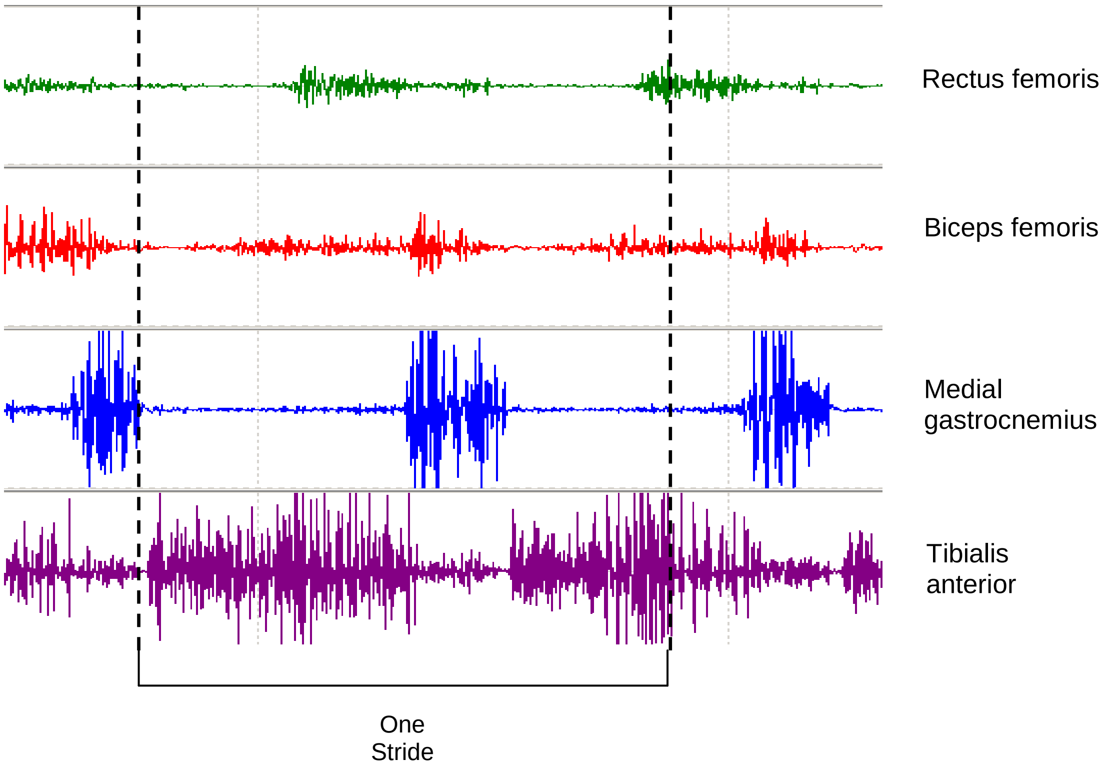


Figure 4: Raw EMG trace of the right leg in relation to gait cycle during normal, unloaded forward walking, taken from the current study.

When referring to Figure 4, Tibialis anterior activity is greatest at heel strike (at the start of the stride) to aid in dorsiflexion and inversion of the foot. The central part of the stance phase generally reveal no Tibialis anterior activity, while a second peak at toe-off of the stance phase corresponds to dorsiflexion of the ankle, allowing the toes to clear the floor. Tibialis anterior works synergistically with extensor digitorum longus and extensor hallicus longus to control dorsiflexion (Perry, 1993).

Gastrocnemius activity begins at heel off to provide the propulsive power behind the step, being the main planterflexor along with soleus (Perry, 1993). This typically ceases at toe off. Rectus femoris (currently representing the quadriceps group) typically contracts in the latter stages of knee extension (early knee extension is thought to be part of a passive swing) and in the end of the stance phase to fix the knee in extension before toe off. Rectus femoris is typically a hip extensor and knee flexor and operates in conjunction with iliacus, adductor longus, sartorius and gracilis (Perry, 1993). Biceps femoris (representing the hamstrings group) contracts at the end of flexion and start of hip extension to terminate and prevent further hip flexion before heel contact and to assist the body over the stance limb. Perry (1993) further suggests that the hamstrings contract at 30% MVC during the terminal swing phase. This phasic timing is demonstrated in Figure 4 where Rectus femoris (quadriceps) activity peaks prior to Biceps femoris (hamstrings), with rectus femoris occurring during the stance, and biceps femoris during the swing phase. The relationship of the timing of muscle activity during normal walking as opposed to during push/pull activities is as yet unknown.

Theoretical electromyography

Some discussion of electromyography (EMG) is integral to the current study as although it is very useful from an ergonomic point of view, there are several factors to be considered in order for it to be used correctly and to accurate effect. Hillstrom and Triolo (1995) define EMG as the “electrical manifestation of the contracting muscle” and state that muscle contraction cannot be elicited without a corresponding electrical EMG signal. Furthermore the physiological processes involved in muscle activation allow for the EMG signal to be a valid indicator of muscle activation level and that certain connections are likely to exist between the magnitude of EMG signal and the exerted muscle force (Kleissen **et al**., 1998). When discussing the uses of EMG in ergonomic applications, Marras (1992) highlights its value for analysing the performance associated with the workplace, particularly when investigating whether specific muscles are being adversely affected by the design of a workplace. Ergonomic EMG methodology recording techniques typically use surface electrodes as opposed to fine-wire intramuscular electrodes.

While surface EMG is simpler and therefore more widely used, it remains important to acknowledge its limitations. When superficial muscles are to be studied, surface EMG is adequate, indeed preferable, however this method does not allow for recording EMG signals of deep muscles (Soderberg and Knutson, 1995). In this situation it is important to consider ‘cross talk’ whereby signals from muscles other than those being considered are recorded at the electrode site

(Perry, 1992). Surface EMG is also affected by electrode geometry, distance between active fibres and the electrode as well as the location on the muscle (Kleissen **et al.**, 1998). In this way, placement of the electrodes becomes essential to the validity of the data collected, as any deviation from the original position is likely to result in different muscle activation results. Soderberg (1992) highlights the importance of standardising factors such as the size and type of electrode, inter-electrode spacing and location (relative to anatomical landmarks) in order to improve reliability of the measure. A further issue is that of normalisation, a process that is required to allow comparison between individuals by providing a standard of reference (LeVeau and Andersson, 1992).

Normalisation

LeVeau and Andersson (1992) suggest that varying amounts of information can be acquired from EMG depending on the interpretation of the EMG signal and detail several ways that this signal can be analysed and interpreted. These authors further explain that as there is not a strict one-to-one relationship between myoelectric signal amplitude and contraction force, there is a need to establish a benchmark to allow comparison between individuals, a process known as normalisation.

The most common of these methods is to perform a reference contraction, an isometric maximal voluntary contraction (MVC). Following this, the myoelectric signals are expressed as a percentage of the MVC (%MVC). Although errors remain with reference to the amount of force produced not maintaining a completely linear relationship with myoelectrical output, authors such as Komi and Viitasalo (1976) indicate that MVC is an acceptable means of standardising. With particular reference to gait research, Perry (1992) writes that normalisation using a maximal effort test (MVC) is widely used and acceptable as a means of differentiating the intensity of effort among muscles. This method has some limitations when considering dynamic activities; the length-tension relationship and location of firing motor units does not remain constant as it does during isometric activities. However LeVeau and Andersson (1992) advise that this method may still be utilised with success if investigators are aware that in many cases the myoelectric signal will give an overestimation of the maximum force.

Furthermore researchers have found that intra-individual comparison is more valid than inter-individual comparisons as a direct result of the small intra-subject variations and large inter-subject variations that occur during investigations of muscle activity (Lawrence and DeLuca, 1983; Yang and Winter, 1983). Soderberg (1992) advises that between individual comparisons are precluded on the basis of differences in instrumentation and body tissue components of different body areas. When applying the results of EMG investigations, it is fundamentally important to consider the limits associated with the technique in order to ensure accurate interpretation and application of these results.

EMG within gait research

EMG is widely used in Ergonomic research as it allows relatively easy access to some previously unobservable physiological processes which are fundamental to force production, underlying all human movement (DeLuca, 1993). In conjunction with gait analysis, EMG has been used in investigation of pathological gaits (Kleissen **et al.**, 1998) rehabilitation (Ricamato and Hidler, 2005) and examining 'normal' walking patterns (Kleissen **et al.**, 1998). Campanini **et al.** (2007) advocate surface EMG as particularly useful in determining the relative contribution of superficial muscles that act during walking. Whittle (1991) comments on the value of EMG within gait research, if the individual is allowed to walk freely, thus encouraging the use of telemetry.

There is as yet no consensus at to the pattern of muscle activity that takes place during the gait cycle due to inter-individual variation; however it is acknowledged that during gait most muscles have large bursts of activity for brief periods, mostly during transition between the swing and stance phase (Oatis, 2004). Perry (1992) offers an extensive explanation of the typical muscle activity patterns that occur in the lower limb and further explains how the timing of muscular activity is key in identifying normal and pathological gaits.

As with any EMG research, there is a degree of variation between muscle activity results, however with specific reference to gait Grasso **et al.** (1998) cite sample differences in sex, age and physical fitness as a cause. Furthermore these authors suggest that variation in normalisation of the muscle activity data would account for these differences. Thus researchers must be aware of these issues when contemplating results obtained from EMG studies, particularly with reference to gait.

Walking, balance and ST&F accidents

Winter (1995) suggests that human bipedal locomotion inherently creates a challenge to our balance control system. The author continues, saying that this is not only a result of having only one foot in contact with the ground during most of the gait cycle (walking), but also as the majority of the mass of the body is approximately two thirds of one's stature above the ground. This has been particularly recognised and researched with respect to elderly individuals where falls due to loss of balance while walking are a major cause of bone fractures and even death (Holbein-Jenny **et al.**, 2007). The stability of walking varies throughout the gait cycle, depending both on the degree of foot contact with the ground and the posture adopted (England and Granata, 2007). During walking the centre of mass is constantly outside the base of support, apart from the short periods of double support, and as a result has been termed 'dynamic balance' (Winter, 1995). Accordingly the body must constantly be counteracting gravitational forces to avoid the chance of falling. This process is further complicated when one is required to produce force while walking, such as occurs during dynamic pushing and pulling. Individuals are increasingly stable as the amount of double support increases as a percentage of the gait cycle as this increases their base of support. Increased walking velocity leads to decreased double support contact times and individuals become inherently less stable (Winter, 1991; Stoquart **et al.**, 2008). This has implications for pushing and pulling tasks as it may be difficult to move heavy loads at high speeds due to these stability issues.

PSYCHOPHYSICAL RESPONSES

It is argued that monitoring of subjective feelings of discomfort is important not only as a central consideration of individual perceptions of a work task, but also as an indicator of potential risk for musculoskeletal disorders (Evans and Patterson, 2000). Individuals may experience feelings of discomfort in different areas as a result of individualised human nature. Kumar **et al.** (2000) write that perceptions of a work task are subjective such that they are influenced by more than biomechanical and physiological factors. A commonly used method of assessing this in Ergonomic evaluations is that of the Body Discomfort map (see Appendix B) which is modified from Corlett and Bishop (1976). Corlett and Bishop (1976) explain that discomfort is the total of unpleasant sensations received from all the different body areas. Discomfort indicates an incompatibility between the worker and the task and can be used as an indicator of problem areas of potential musculoskeletal disorder risk. This is a useful ergonomic tool as it allows for identification of specific areas where discomfort is experienced and, in addition to this, intensity of the discomfort can further be rated. The reliability of perceptual scales is dependent on the participant receiving clear and detailed explanations such that they have a thorough understanding of the concept and the use of the rating scale.

CONCLUSION

Pushing and pulling research has proved intricate, yet remains fundamental in allowing ergonomists to design and modify work situations such that they do not place excessive demands on the human worker and result in injury or lowered efficiency. An integral element of dynamic pushing/pulling is walking, and as such examination of the gait and lower limb muscle activity patterns induced during these activities may aid in determining the strain that workers are experiencing, as well as identifying potential slip, trip and fall risks. The complex interaction of factors affecting pushing/pulling has led to a growing body of research literature, yet it remains fundamentally necessary to further the understanding of the multifaceted relationship between pushing/pulling and associated physical and perceptual demands.

CHAPTER III

METHODOLOGY

INTRODUCTION

In 1993 Daams suggested that a consensus on acceptable loads for pushing/pulling tasks had not been reached due to vastly different methodologies being employed within push/pull research. This lack of agreement remains; the complex nature of push/pull research allows for numerous interpretations and experimental procedures, thus it is still difficult to compare results from various push/pull investigations. Furthermore, there are a host of extraneous factors that need to be controlled in push/pull research. Rigorous standardisation is therefore necessary to limit the impact of these extraneous variables (Mack **et al.**, 1995; Jung **et al.**, 2005). Literature has shown that the most widely used psychophysical guidelines set by Snook (1978), and subsequently redeveloped in 1991 (Snook and Ciriello, 1991), have been debated on methodological issues (Resnick and Chaffin, 1995; Shoaf **et al.**, 1997). This is not to suggest that the guidelines are ineffectual, as they have allowed for a degree of control on work situations to reduce task demands, however it serves to highlight the complexity of methodological issues within physical ergonomic research. The intricate array of factors affecting pushing/pulling illustrate that if conclusions are to be successfully implemented in industry, they must display sound methodological reasoning for increased validity and reliability.

PILOT TEST PROTOCOL

With cognisance of the many methodological issues surrounding the combination of pushing, pulling and gait research, and in light of the lack of literature in the area, the current study undertook extensive pilot testing. Several key issues had to be examined to ensure that the study was methodologically sound. Furthermore this process allowed familiarisation with the equipment and procedures to be used throughout experimentation.

Walkway distance

With respect to the push/pull component of the study, it was important to ensure that the distance over which the load was moved was adequate to gain representative results, yet not so long as to fatigue the individuals. Additionally the selected distance had to allow for discernment of the three motion phases as well as permit sufficient strides for valid gait analysis. Push/pull literature includes an array of distances between 0.24m and 15m used for dynamic testing (Resnick and Chaffin, 1995; van der Beek **et al.**, 2000; Ciriello **et al.**, 2001; Schibye **et al.**, 2001; Haslam **et al.**, 2002); during pilot testing various distances between 5 and 20 metres were examined and a distance of 10m was selected. This distance was sufficient for the collection of biomechanical responses without inducing fatigue in the individual and thus ensuring valid responses.

Acceleration/deceleration

It has been shown that acceleration/deceleration is an integral factor in initial/ending hand force magnitude (Resnick and Chaffin, 1995), and thus it is important that it be meticulously controlled to reduce intra-subject variability. Demarcation of a specific area at each end of the walkway controlled the distance over which the initial acceleration and final deceleration were performed. Distances of 0.5m, 1m, 1.5m and 2m were tested and 1.5m was chosen for each end of the designated walkway. These areas were demarcated with highly visible marking tape. The 7m distance that remained was indicative of the sustained phase of movement where pilot studies showed individuals were able to maintain a consistent speed. This sustained phase distance furthermore corresponded to similar distances utilised in prior gait and push/pull research (Ericson **et al.**, 1986; Resnick and Chaffin, 1995; Ciriello **et al.**, 1999b; Jansen **et al.**, 2002). Pilot studies revealed that it was important to clearly inform participants as to the technique to use for acceleration/deceleration to reduce variability in technique.

Walking velocity

A common factor integral to push/pull (Eastman Kodak, 1986; Jansen **et al.**, 2002; Jung **et al.**, 2005) and gait research (Basmajian, 1974; Whittle, 1991; Oatis, 2004; Chiu and Wang, 2007) is that of walking speed. Walking velocity influences the hand forces required, temporal and distance components of gait and muscle activity (Winter, 1991; Stoquart **et al.**, 2008). Furthermore muscle activity varies significantly with walking speed (Oatis, 2004; Stoquart **et al.**, 2008). In the few push/pull studies that controlled walking velocity, speeds of 0.2 $m.s^{-1}$ to 1.12 $m.s^{-1}$ were applied (Eastman Kodak, 1986; Lee **et al.**, 1991; Resnick and Chaffin, 1995) although high velocities were related to increased risk of slipping. In order to allow for valid comparison between individuals, walking speed was relativised to stature as is standard in gait studies.

A variety of speeds were tested, ranging between 0.3 statures.s^{-1} and 1.1statures.s^{-1}. At the lowest speeds an exaggerated and uncomfortable gait pattern was reported, while the highest speeds could not be maintained when moving the heavier loads. Of the speeds tested during piloting, those of 0.45-0.55 statures.s^{-1} (approximately 0.4-0.5 m.s^{-1}) were selected as the most preferable. The speed selected is classified by Charteris (1982) as ‘slow’. However given the added requirement of moving a laden trolley, this speed was determined to be realistic and therefore applicable to industry without the risk of injuring participants.

Muscle activity

Literature relating to lower limb muscle activity during normal walking (both forward and backward) is available, however is sparse in the area of pushing and pulling. Pilot studies were conducted, taking into account the actions of the various muscles and their relationship to the gait cycle. These muscles included Rectus femoris, Vastus medialis, Biceps femoris, Semitendinosis, medial and lateral Gastrocnemius, Soleus and Tibialis anterior. Examples of raw EMG tracings from selected pilot studies can be seen in Appendix C. The nature of EMG testing necessitates the limitation of muscle numbers in a given body area as too many cables create excessive noise, resulting in inaccurate responses (Goebel, 2005). Thus the muscles with the most significant response, along with consideration of their accessibility to surface EMG electrodes, were chosen. Whittle (1991) proposed that when using surface EMG a high degree of ‘crosstalk’ from adjacent muscles occurs and as a result the muscle activation signal should be seen as derived from muscle groups rather than a specific muscle.

The pilot studies furthermore established that muscle activity was similar for both legs during the sustained phase. During the initial phase, greater EMG activation was observed on initiation of the movement in the ‘driving’ leg used to push off, with lower activation occurring in the trailing leg during the first step. In light of similar EMG responses and to reduce possible interference from cables, data were collected on one leg only, with this being the leg that was used to initiate movement. In order to standardise the leg that would be used for push off, the starting position needed to be controlled in each technique. A variety of foot placements (both staggered and non-staggered) were undertaken, with a clear preference to the driving foot placed posteriorly when staggered.

Load mass

Central to manipulation of task demands, it was important to establish the choice of load mass. Several loads were applied during pilot studies, with the aim of allowing significant responses to occur while not putting participants at risk of injury. Adequate maintenance of the pallet jack and acceptable wheel-floor friction in the current study created an 'ideal' work situation whereby results would set an upper limit from which industry could determine acceptable load mass. The linear relationship between load mass and force exertion suggested that two loads would be suitable; an upper load of 500kg proved unlikely to injure participants while remaining reflective of real work demands. Heavier loads were not used as 500kg was heavy enough to elicit significant biomechanical responses; it was also unethical to place participants under greater strain than was necessary. From this a lighter load of 250kg was then chosen.

Choice of manual handling device

Push/pull literature yields a variety of wheeled devices, including two wheeled trolleys, four wheeled aircraft food trolleys, sack trucks, pallet jacks and wheeled dustbins (Mack **et al.**, 1995). The current study undertook to use a four wheeled pallet jack (Pallet of 0.97 x 1.22m; back wheel diameter: 0.17m, front wheel diameter: 0.08m). This kind of pallet jack is commonly used in South African industries for moving heavy loads; furthermore it meant that the loads remained identical throughout the data collection period as each load could be placed on a separate pallet, thus circumventing the chance of human error that may occur with load changes.

Through pilot testing it was seen that a habituation session would be necessary to allow participants who were not previously exposed to push/pull tasks to practice steering the pallet jack such that they would not go off the sides of the walkway.

This further allowed participants to practice acceleration/deceleration in the demarcated areas prior to testing.

EXPERIMENTAL DESIGN

As this study determined to investigate the effect of load and push/pull technique on hand force, muscle activation, gait pattern and psychophysical responses a combination of loads and techniques were utilised. Jung **et al.** (2005) suggested that of the four common methods of pushing/pulling, backward pushing is least employed in the workplace. The following remaining techniques were used in the current investigation; bilateral forward pushing, unilateral forward pulling (using the dominant hand) and bilateral backward pulling.

In industry loads of up to 1500kg have been evidenced (Mack **et al.**, 1995), however authors such as Resnick and Chaffin (1995) have set acceptable limits at 225kg. Li **et al.** (2008) report cumulative load weights of between 300 and 4400kg being moved on pallet trucks. These authors utilised loads of between 295kg and 568kg to investigate slipping while pushing/pulling. As load increases, so does force exertion and physiological responses (Datta **et al.**, 1978; Datta **et al.**, 1983; Resnick and Chaffin, 1995; Haslam **et al.**, 2002) and a linear relationship between load mass and force exertion have been found, dependent on the characteristics of the workplace (Donders **et al.**, 1997; van der Beek **et al.**, 2000; Bennett **et al.**, 2008; Cripwell, 2007). Furthermore limits on load mass may be modified by aspects such as distance travelled, trolley maintenance and wheel-floor co-efficient of friction. Subsequent to pilot studies, a lower (250kg) and higher (500kg) load were chosen, and the three techniques suggested by Jung **et al.** (2005) were performed at each of these two loads.

In order to gain an understanding of the added lower limb muscle activity and gait pattern changes associated with pushing/pulling, two further control conditions were included in the experimental design in the form of normal unloaded forward and normal unloaded backward walking protocols. These were performed under identical circumstances to the experimental conditions, with the single alteration of removing the push/pull component. This resulted in a combination of six conditions with two control conditions shown in the design matrix of Table II.

Table II: Matrix of experimental and control conditions.

	Technique		
Load	2 handed forward push	1 handed forward pull	2 handed backward pull
250 kg			
500kg			
Control	Unloaded forward walking		Unloaded backward walking

Each condition involved subjects performing a dynamic pushing/pulling task over the 10 m distance, with each trial lasting approximately 12 seconds. As discovered in pilot studies, to reduce variability in start/stop technique, participants were instructed as to the correct means of initiating and terminating movement during the habituation session and reminded periodically during experimentation. These individuals were instructed to focus on not using a jarring acceleration/deceleration technique, both to reduce variability and risk of injury. The initial 1.5m allowed the participant sufficient distance in which to accelerate the pallet jack such that at the start of the sustained distance they were at a constant velocity; this they were required to maintain for the phase. Similarly the 1.5m distance at the end of the walkway allowed subjects sufficient time to decelerate the pallet jack using a fluid movement. These areas were clearly demarcated. The remaining 7m sustained phase allowed for collection of gait data from no fewer than five complete strides. The aforementioned allowed for valid gait analysis and concurs with previous research (Murray **et al.**, 1964; Dubo **et al.**, 1976; Grasso **et al.**, 1998).

The testing was performed on a ply-wood walkway (2.44m wide), similar to that described by Ciriello **et al.** (2001), allowing for sufficient foot-floor friction to discourage slipping. A walking velocity of 0.45-0.55 statures.s^{-1} was controlled by use of LEDs (placed next to the walkway) and a desktop computer; walking velocity was thus collected for each trial and rigorously controlled. The means for assessing walking velocity, in the form of the LEDs, were built in the Department of Human Kinetics and Ergonomics for the purpose of this study. Three successful trials of each condition were performed, and approximately 60s of recovery was given between each trial and a longer break between conditions when the load was changed. Fatigue and undue musculoskeletal strain were therefore unlikely. In the case of an unsuccessful trial, one where the speed was not kept between 0.45 and 0.55 statures.s^{-1} in the sustained phase, subjects were required to repeat the trial.

When considering the responses observed, a total of four muscles were chosen, which represented the four major muscle groups in the lower extremities. These muscles included Rectus femoris (RF), Biceps femoris (BF), medial Gastrocnemius (MG) and Tibialis anterior (TA). These muscle choices are supported by the literature; MG and TA are the main dorsi and plantor flexors of the foot and play critical role in propulsion during walking (Murray **et al.**, 1985; Perry, 1992; Chiu and Wang; 2007). Perry (1992) indicates that the activity of the RF and vasti differ, however RF was chosen due to accessibility and its role in knee extension (Murray **et al.**, 1985). Activity of the hamstrings group (BF, semitendinosus and semimembranosus) is typically uniform in knee flexion (Basmajian, 1974; Perry, 1992) such that any single muscle represents the group, however the BF is more easily accessible for surface EMG. Murray **et al.** (1985) and Whittle (1991) concur that surface EMG can be used as an indicator of whole muscle group exertion (as opposed to specific muscles) and this further supports the current study’s choice of muscle recording sites; they allow for a general indication of muscle use in the lower extremities.

Muscle activity responses were only collected on one leg, this being the dominant one (right leg in a right hand dominant sample group). To control starting posture and standardise initial muscle force responses, foot placement was controlled to be staggered, with the right foot situated posteriorly. Thus in each trial the right leg was the ‘driving’ one for push off, seen to elicit the highest muscle activity responses.

Following a habituation session, participants were required to attend a single testing session, lasting approximately ninety minutes. It was decided to complete testing in one session as EMG readings are vastly affected by electrode placement and maximal voluntary contraction (MVC) recording, both of which may greatly vary between several experimental sessions (Campanini **et al.**, 2006). By completing testing in a single session, reliability and validity of EMG recordings was increased while sufficient rest periods ensured that the participants did not become fatigued by the experimental conditions.

MEASUREMENT AND EQUIPMENT PROTOCOL

Biophysical measures

Hand forces

Horizontal hand forces were measured using the Chatillon^{TM} DFS-R Series Force Gauge with Dedicated Remote Loadcell which was capable of measuring real time tensile and compressive forces with a measurement accuracy of 0.1% full scale. The forces recorded by the dynamometer at the trolley handle are indicative of those required by the operator to move the load and can specify phases in which the operator might be exposed to risk of injury resulting from the requirement of excessive force production. The loadcell was vital in identifying the separate motion phases and allowing the researcher to indirectly investigate the biomechanical strain being placed on the operator by the push/pull tasks.

The pallet jack used in the study was modified to allow for the attachment of the Chatillon^{TM} to the handle of the pallet jack (Figure 5). As a result participants were required to utilise the modified Chatillon^{TM} adaptor handle as the alternative grip; this allowed for collection of forces but did not compromise the steering or control of the load. Furthermore the pallet jack handle was fastened in the upright position to allow for the accurate collection of horizontal hand force exertion, as well as for ensuring easier steering of the pallet jack on the walkway.

Figure 5: Modified pallet jack handle with Chatillon^{TM} load cell attachment.

Forces were recorded instantaneously at a sampling rate of 5000Hz and stored on a laptop computer. The Nexygen DF Series software package presented data graphically and numerically, allowing for real time feedback to the researcher during the experimental conditions. For graphical presentation the software automatically smoothes the data such that the resulting graph does not display all data points (Figure 9). The laptop was placed on the pallet jack during experimentation and was incorporated into the load weight. The raw data was processed using the DataAnalysis tool, developed in the Human Kinetics and Ergonomics Department at Rhodes University, and used pattern recognition technology to identify each push/pull into the separate phases. The software identified each cycle, and within each cycle the initial and ending peaks; between these the force was averaged to provide the sustained phase. This tool allowed for further assessment by delivering mean peak initial, average sustained and mean peak ending forces for each individual trial.

Gait responses

Basic gait measures were taken to determine stride length in the sustained phase by counting the number of steps taken between points demarcated clearly on the walkway. In order to decrease counting error, the counting practice was standardised such that steps were taken as being in the prior phase if the step crossed a demarcated line (initial-sustained and sustained-ending).

Previous research into gait (Charteris, 1982; Nottrodt **et al.**, 1982) has used the heel, lateral ball, medial ball and toe as key placement landmarks on the foot, thus these landmarks were used for the current research. More sophisticated gait data were recorded using a system designed in the Human Kinetics and Ergonomics Department. This made use of Tekscan FlexiForce A201 Variable Resistance Sensors (45.5kg pressure limit). These are similar to footswitches in that they record pressure changes, thus indicating when pressure is placed on them. Whittle (1991) advocates the use of footswitches mounted in shoes to indicate when various parts of the foot are in contact with the ground. In order to mimic industrial settings as far as possible, standard Rhodes University maintenance issue work boots (Lemaitre Securite^{TM} Safety Footwear) were used in this study. These are steel capped and anti-slip boots and would be commonly found in industry in South Africa. Sensors were placed between innersoles of the work boots at 10% (heel), 55% (lateral ball), 70% (medial ball) and 90% (toe) of the shoe length (See Figure 6).

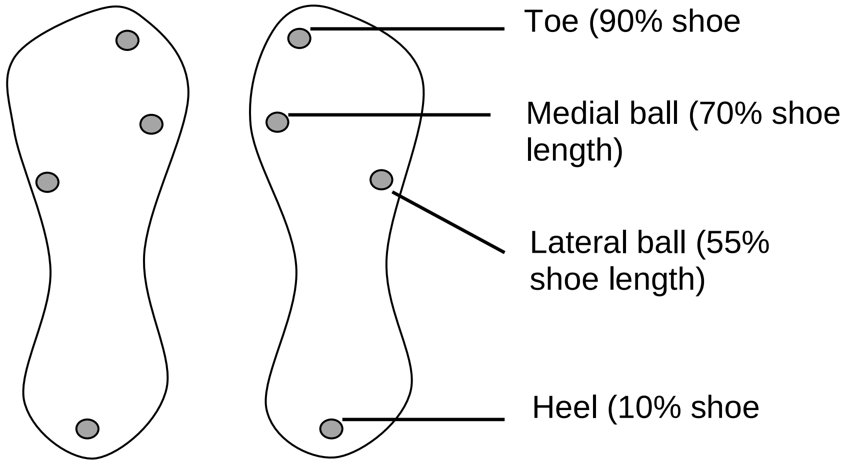


Figure 6: Placement of contact sensors under innersoles of left and right shoes.

The extensions of the resistance sensors were threaded out of small incisions made in the fabric of the work boots and then glued to the external surface of the shoe to ensure stability and connected to the Biometrics Ltd DataLOG W4X8 Bluetooth$^{®}$ (Biometrics Ltd, Nine Mile Point Ind. Est, Gwent, NP11 7HZ, United Kingdom) via cables that were secured to the back of the legs such that they would not impede movement, illustrated in Figure 7.

Figure 7: Work boots used in the current study illustrating (a) the built in contact sensors with (b) connection to the DataLOG.

The data from the foot contact sensors was collected on the Biometrics Ltd DataLOG W4X8 and relayed via a Bluetooth link to a laptop where it was stored. The Biometrics Display & Analysis Software allowed experimenters to follow progress in real time. Channel sensitivity was set at 1V, the sensor sampling rate set at 500.s^{-1} with an excitation output of 1000mV. Three pairs of shoes were modified for placement of the sensors (sizes 9, 10 and 11) and all subjects in the current sample utilized one of these three sizes to ensure standardisation. Sensors remained in place throughout the experimental period, thus minimising errors that could be caused by position change.

Two light emitting diodes (LEDs) and associated mirrors were erected across the testing walkway at approximately mean sample shoulder height. These LEDs were placed 6m apart, within the demarcated 7m area of sustained movement. As participants crossed the LEDs, the velocity between these points was calculated and displayed on a desktop computer. Participants' anthropometric details entered into the GAITrite software allowed the computer to determine relative velocity. The trial was determined to be acceptable if the mean velocity calculated was in the 0.45-0.55statures.s^{-1} range. The use of these LEDs as a means of measuring walking velocity has been validated (Charteris, 1982).

Muscle activity

The Muscle Tester ME6000 Biomonitor System (Mega Electronics Ltd) device was utilised in order to gain information regarding the electrical activity of the muscle through surface electromyography (EMG). This was achieved by placing two active electrodes in a bipolar arrangement, with a neutral electrode on passive tissue as advocated by Goebel (2005). Standard placement of the electrodes in the current study was ensured by using anatomical landmarks (Kendall **et al.**, 1993). In order to prepare the area of skin on which the electrodes were to be placed, the hair was shaved and the skin wiped with an alcohol solution. Two disposable, pre-filled Silver Chloride electrodes were attached parallel to the muscle fibres above the belly of the muscle, a distance of 5 cm apart. A neutral electrode was placed above an inactive muscle; cables were then attached to these electrodes and the ME6000 Biomonitor System to allow for the collection of EMG data.

As a means of normalisation, maximal voluntary contractions (MVCs) were performed during the experimental session, prior to the experimental conditions. The MVC testing followed standardised protocol as detailed by Kendall **et al.** (1993) and followed the same order in each case (see Appendix C). Each MVC was performed twice and maintained for a total of five seconds each time to ensure a sustained maximal response.

A telemetry system allowed normal movement, with the Muscle Tester device being portable and non intrusive, such that the participants were able to perform the task unhindered by heavy or bulky equipment. The gait responses were then collected via telemetry on a laptop, allowing easy monitoring of the data during experimentation. The Megawin© software programme was used for processing and collecting the raw data. The sampling rate was set at 1000Hz with a sensitivity of 1µV. Processing of data was performed post-experimentation using the DataAnalysis software package developed in the Human Kinetics and Ergonomics Department. This software provided the mean amplitude of the muscular activation during a specified work period.

Psychophysical measures

Body Discomfort Map

The Body Discomfort (BD) Map, developed by Corlett and Bishop (1976) was used to provide a more holistic view of the effect that the experimental conditions had on the individual. Monitoring of discomfort is important for two reasons, firstly it is an indicator of potential risk for musculoskeletal problems and secondly, according to Evans and Patterson (2000), it is central when considering individual perceptions of a work task. The BD map (see Appendix B) is an illustration of 27 body segments located on the anterior and posterior of the body. A scale of 1 (very slight discomfort) to 10 (extremely uncomfortable) is provided as an indication of discomfort level. After each experimental condition, the participant was required to report on a maximum of three areas (the three incurring the most discomfort) in which any discomfort occurred during the task and then to rate its intensity. Participants were allowed to give no BD ratings if they felt that the task was not causing any discomfort at all.

EXPERIMENTAL PROCEDURE

Habituation

Prior to testing, participants were required to attend a habituation session in which the procedures and equipment to be used were fully explained together with some background information regarding the context of the investigation. Participants were welcomed; background to the study, equipment to be used and the experimental process were then fully explained to the individuals. The use of the psychophysical ratings was subsequently fully explained and the group were encouraged to ask questions if clarification was necessary.

On completion of this phase, individuals were asked to read a letter of information and sign informed consent (Appendix A). Following this, demographic and anthropometric measures were recorded; these included stature and mass for means of determining the sample population characteristics. These measures, as well as age and hand dominance, confirmed the participant eligible to be included in the delimitated group, thus ensuring that the sample group was as homogenous as possible.

In order to guarantee that participants were comfortable with the experimental conditions, they were each habituated to the testing conditions to the satisfaction of both themselves and the researcher. Each participant was required to don the correctly sized work boots and then practice each of the three push/pull techniques. In all cases, the researcher gave full instructions of the acceleration/deceleration technique required to avoid jarring movements. The correct starting position, with specific foot placements was explained and performed for each technique. Stature measures were entered into the relevant software package and the researcher then indicated correct walking speed to the subjects. The habituation was only completed once the participant was able to walk at the correct speed while pushing and pulling the cart using the appropriate technique. Extensive habituation was performed as pilot studies indicated that numerous practice trials were required for subjects to be able to master correct walking speed and start/stop technique.

Experimental session

On arrival at the testing session, the participant was welcomed and the experimental process and body discomfort scale were explained once again. The electrode placement areas were prepared and electrodes were placed on the Rectus femoris, Biceps femoris, medial gastrocnemius and Tibialis anterior muscles using anatomical landmarks as reference points. The electrodes were then attached to the ME6000 Biomonitor System via cables and the portable unit was then clipped comfortably around the participant’s waist. Following this, maximal voluntary contractions (MVCs) were performed on the four muscles whereby maximal isometric muscular contraction was elicited by the participant, aided by a research assistant; some examples of this can be seen in Figure 8. Two research assistants were present throughout testing; these assistants performed the same roles for each habituation and testing session to ensure standardisation.

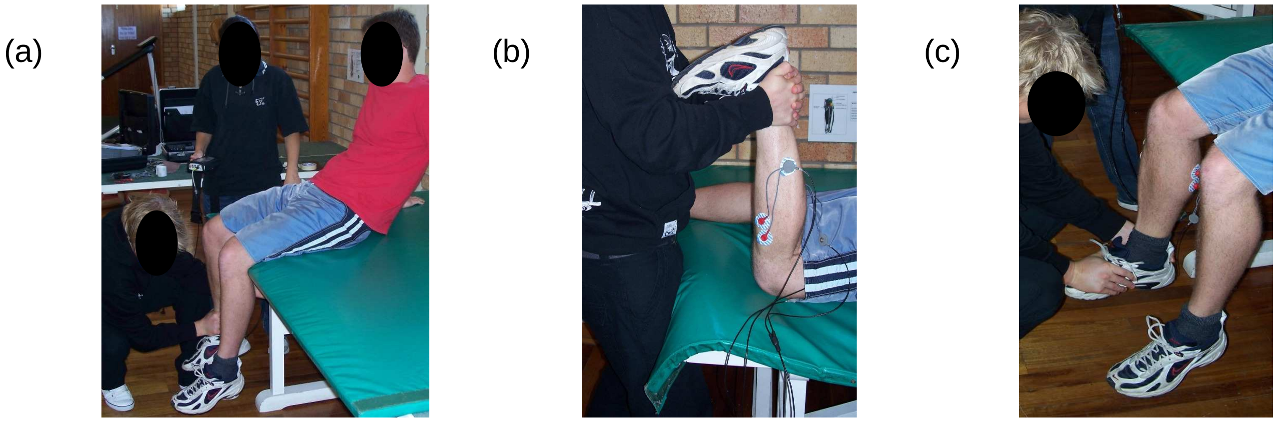


Figure 8: Maximal voluntary contractions (a) Rectus Femoris, (b) Biceps femoris and (c) Tibialis anterior, based on Kendall **et al.** (1993).

On completion of the MVCs, participants donned the shoes containing the pressure sensors, the experimenter then attached the cables from the Biometrics Ltd DataLOG W4X8 to the sensors via connectors on the posterior of the shoe; thereafter the DataLOG was strapped around the waist. All cables were secured to ensure that they did not interfere with the normal walking process.

Before experimental conditions were performed, the participants were required to perform the control conditions of walking forward and backward along the walkway, unloaded. Speed, walking distance, acceleration and deceleration distances were all kept identical to experimental conditions to allow for valid comparison. After a short rest the experimental conditions began. Conditions were randomised such that the 250kg and 500kg loads were alternated to reduce the chances of fatigue and to stop an order effect from occurring. The pallet jack was moved into position by the experimenter and the participant was instructed as to the push/pull technique to use. Once the start position was standardised, the experimenter verbally signalled the participant (“Ready, three, two, one, go”) to begin the trial and then provided verbal feedback as to the walking speed during the 10m trial.

On completion of the trial, a research assistant recorded walking speed and indicated if the trial was acceptable or not. The trial took, on average, 10-12 seconds, and the participant was allowed to recover while the experimenter returned the pallet jack to the starting position. In the event of an unsuccessful trial (when speed did not fall into the specified range), the participant was required to repeat the trial until three successful trials were recorded.

On completion of the three successful trials for one experimental condition, the participant was asked to rate BD, after which they were allowed to sit down and rest. During this time the load was changed to prepare for the next condition, taking approximately eight minutes, leaving the participant with adequate rest to ensure fatigue did not affect the results. Sufficient rest breaks were given throughout the experimental session, with an average work rest ratio of 1:4 (15 s of work to 60s break) and these were increased between push/pull conditions. This was deemed sufficient as van Dieen and Oude Vrielink (1998) recommend ten minutes rest for each hour worked to limit the cumulative effect of postural and muscular load experienced. Furthermore the infrequent nature of the push/pull tasks further reduced chances of fatigue.

Subject characteristics

The sample consisted of 36 male volunteers drawn from the Rhodes University population, all physically healthy and active individuals. During the habituation session several anthropometric and demographic details were recorded and are detailed in Table III.

Table III: Subject anthropometric and demographic characteristics (N=36).

Variable	Mean	SD	CV (%)
Age (years)	21	2	10
Stature (mm)	1791	43	2
Mass (kg)	77	10	12
Elbow height (mm)	1118	37	3

SD = standard deviation; CV = coefficient of variation

Subjects participating in this study had an average age of 21 (±2) years, statures averaged 1791 (±43) mm while mean body mass was 77 (±10) kg. A mean elbow height of 1118 (±37) mm shows that the trolley handle, at 1175 mm, allowed for the participants to comfortably handle the trolley. Furthermore initial posture was standardised such that the starting elbow angle was set at approximately 90^0.

Statistical analyses

Analyses of data were performed using the STATISTICA 8 (Statsoft Inc, 2008) software programme. Initially descriptive statistics were run on all data to test for normality and furthermore obtain mean and standard deviations of responses for all conditions. All data, except muscle activity responses, were acceptable when considering normality. This muscle activity data were therefore transformed using a logarithm and normality tested again; once the data were seen to be normally distributed, statistical procedures were subsequently executed. Two way ANOVAs were conducted on the biomechanical responses for hypotheses 1 (a) to determine effects of load and technique on responses. The Tukey post-hoc test was subsequently used on these results to determine the position of differences within the statistically significant responses. With reference to hypothesis 1 (b) one way ANOVAS were performed to determine the differences between the three motion phases. Hypothesis 2 required repeated measures ANOVAs to determine if responses collected during push/pull conditions were significantly different to ‘normal’ unloaded walking responses. Finally student t- tests were performed between the control conditions (normal forward and backward walking) for both muscle activity and gait responses to determine if any differences between responses during these conditions existed.

The statistical responses were tested at a 95% confidence level, thus the criterion for significant differences was set at $p \leq 0.05$ for each of the hypotheses. This was to minimise the chance of making a Type I error (rejecting a true hypothesis). This significance level was maintained throughout statistical treatment of results. For hand force, muscle activity and perceptual measures data from 36 subjects was analysed. However due to equipment failure preventing 6 sets of data from being valid, data from 30 of the subjects was analysed for gait pattern responses; this sample was still large enough to allow valid and reliable results.

CHAPTER IV

RESULTS

INTRODUCTION

Despite the extent of global ergonomic research and increased interest in Ergonomics in industrially developing countries (IDCs), musculoskeletal disorders resulting from excessive physical strain remain prevalent, particularly when workers are involved in manual materials handling (MMH) tasks (Ayoub and Mital, 1989). Dempsey (1998) cautioned against situations whereby task demands exceed worker capabilities as the resulting injuries are costly to individuals, employers and subsequently the general economy. In workplaces where manual movement of loads predominates, many employers, cognisant of the risks associated with lifting and carrying, have undertaken task redesign and replaced these high risk activities with pushing and pulling using wheeled devices and hoists.

Three decades of interest in pushing/pulling activities (Martin and Chaffin, 1972; Datta **et al.**, 1978; Warwick **et al.**, 1980) has not been sufficient to fully elucidate associated task demands. Thus a great deal of uncertainty regarding biomechanical, physiological and psychophysical strain placed on workers remains, despite the fact that they have been recognised as potentially injurious (Hoozemans **et al.**, 1998; Kuiper **et al.**, 1999; van der Beek **et al.**, 1999). Hand forces have been used as an indicator of mechanical loading, although the effects of posture and direction of joint loading should be acknowledged in conjunction with this (Hoozemans **et al.**, 2004). To aid in the clarification of some push/pull task demands, Todd (2005) indicated that gait responses to pushing/pulling activities are integral in determining slip, trip and fall risk as well as possible risk of fatigue. However few researchers have considered this. Furthermore there is scant information concerning the muscle activity responses to pushing/pulling, although this may aid in determining lowered productivity due to fatigue and reduced endurance time (Rohmert **et al.**, 1986). Thus the current study aimed to investigate not only aspects such as the relatively well researched hand force exertion, but also lower limb muscle activity which is integral in both the walking component of the task as well as providing the majority of the propulsive power required to move the load. Additionally gait responses were quantified using direct and indirect methods and further psychophysical responses in the form of body discomfort were included to gain a more holistic view of the worker responses to dynamic pushing/pulling tasks.

HAND FORCE EXERTION

The current study undertook to quantify the horizontally exerted hand forces under the current conditions to determine if these could be used to assess work demands within industrial situations. Hand forces are some of the most easily accessible measures within industry as they require relatively simple equipment and can be gathered without interrupting the work process as other methods would be likely to do.

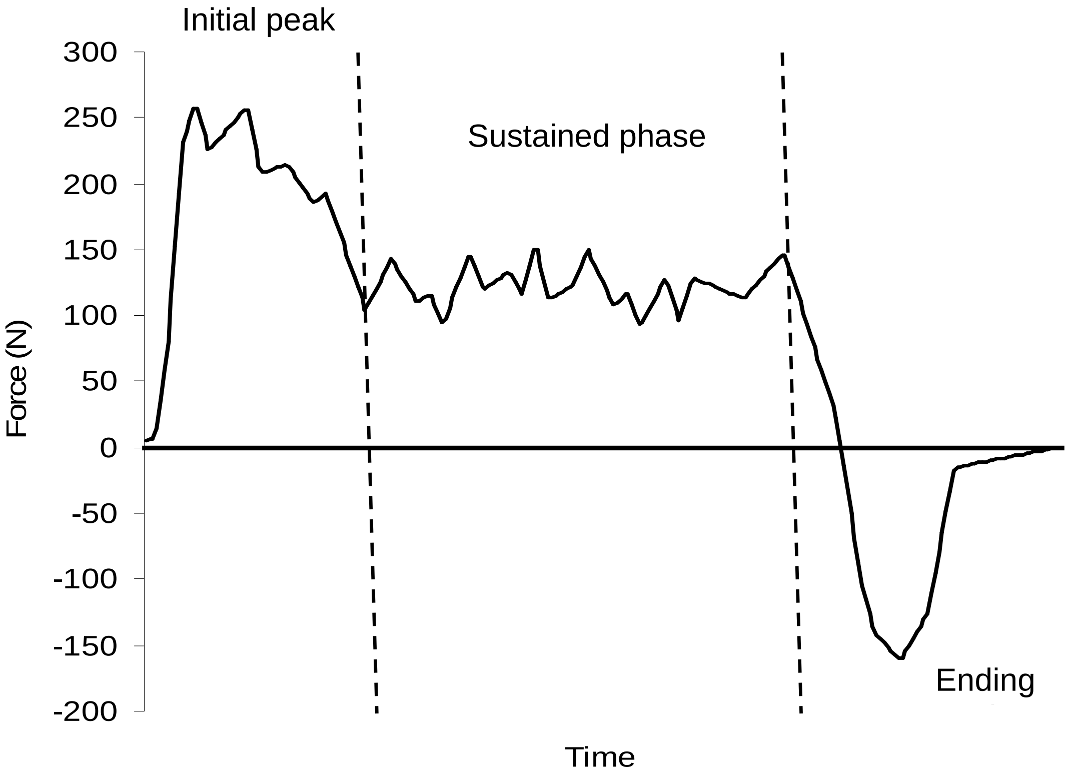


Figure 9: Force graph taken during dynamic push trial (at 500kg), identifying initial, sustained and ending phases.

Of these exerted forces, research has distinguished three distinct motion phases; the initial force required to accelerate the object, the sustained force to maintain movement and the ending force required to stop the object (Snook, 1978; Snook and Ciriello, 1991, Jansen **et al.**, 2002). These phases were evidenced in the current study, an example of which is shown in Figure 9 which displays a smoothed graph of a push trial at 500kg from the current research. Forces examined were the peak initial and ending forces, as well as the averaged sustained forces.

For ease of comparison, statistical analysis and explanation, all hand forces are assessed in absolute terms, however as Figure 9 shows, the ending force always occurs in an opposite direction to the initial and sustained forces. Thus initial and sustained tensile forces during pulling become compression forces during the ending phase; the contrary then applies for pushing.

Peak initial forces

Research indicates that the initial phase creates the highest risk of operator injury as it elicits the greatest peak forces, required to overcome both inertia and the friction occurring between the wheels and the floor (van der Beek **et al.** 1999; Jansen **et al.** 2002). Peak initial forces were investigated in the current study to determine whether these experimental conditions would result in hand forces of magnitudes that could lead to overexertion of the musculoskeletal system. It is hypothesised that there is a relationship between hand forces and muscular exertion; muscular contractions provide the power necessary to move increasingly heavy loads, thus if increased force is required, muscle recruitment will increase, a situation that is likely to result in local muscle fatigue and reduced endurance time (Rohmert **et al.**, 1986).

Effect of load

A variety of push/pull studies have indicated a linear relationship between hand force exertion and load (Resnick and Chaffin, 1995; van der Beek **et al.,** 2000; Haslam **et al.**, 2002; Cripwell, 2007; Bennett **et al.**, 2008). The current study utilised two loads, a lower one of 250kg and a heavier of 500kg to investigate the relationship between load and hand forces. Table IV illustrates the effect of load on initial peak hand forces.

Table IV: Effect of load on mean initial peak hand forces (N) (Standard deviation (SD) in brackets).

	Technique		
Load (kg)	Push	1 H Pull	2 H Pull
250	204 (17) ┐	194 (16) ┐	202 (19) ┐
500	333 (29) ┘	297 (23) ┘	303 (26) ┘

└─┘ Indicates significant differences (p<0.05)

Where Push = two handed forward pushing, 1 H Pull = unilateral forward pulling and 2 H pull = two handed backward pulling

Pushing resulted in the highest hand forces for both low and high loads while, contrastingly, one handed pulling elicited the lowest forces for both loads. The greatest peak forces were evidenced at the 500kg load for all techniques, an obvious result of increasing load. Significantly higher hand forces were recorded at 500kg as opposed to 250kg for the same technique, reflected by p values of <0.05 in all cases. It is interesting to note that although the load is doubled, none of the initial forces at the high loads reach double those elicited at the 250kg load. Increases for pushing, one handed pulling and two handed pulling were 38%, 34% and 33% respectively, thus as load doubled, hand forces increased by approximately a third. Importantly, the variance observed at both loads is constant and relatively low, between 8% and 9% in all cases. This would indicate that individuals were able to move high loads with forces of similar consistency to low loads. This strongly suggests the importance of floor-wheel friction as a predictor of hand forces as this factor remained constant at both loads and thus requires further investigation.

Effect of technique

A second premise of the current study was that technique could play a role in impacting the hand forces; research has attempted to quantify this in an effort to provide empirical research supporting a technique that has a twofold aim: to optimise worker performance and reduce injury risk. Results from the initial peak forces are displayed graphically in Figure 10, considering the effect of technique.

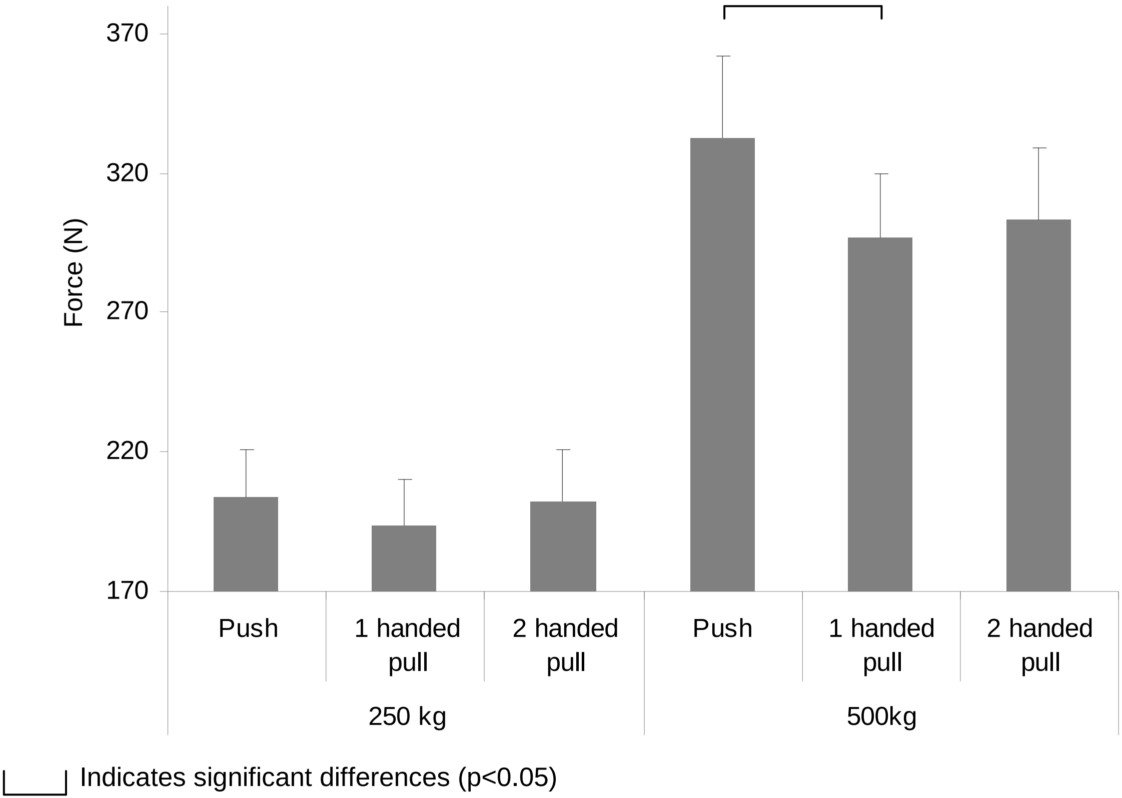


Figure 10: Effect of technique on peak initial forces.

There is no significant difference between techniques in terms of initial peak hand forces at 250kg, with a difference of only 10N between the highest and lowest responses. At 500kg however, Figure 10 shows that pushing elicited significantly higher hand forces than did one handed pulling; a difference of 35N. At both loads, the greatest difference occurred between pushing and unilateral pulling and represented a 7% disparity. This would suggest that at low loads technique does not play a role in determining hand forces, while at the 500kg load, pulling elicits lower hand forces than does pushing. With regards to pulling, during peak initial forces there are no significant differences between one and two handed techniques, thus either technique could be preferable above pushing in terms of reducing hand force exertion.

Average sustained forces

Sustained forces have received less attention in push/pull literature than initial or ending forces due to the significantly lower magnitude of required forces in this phase. Figure 9 (page 55) indicates that the sustained force, while generally of lower magnitude than initial or ending peak forces, is maintained for a much longer period of time. In the current study, initial and ending phases generally occurred over two to three seconds while the sustained phase occurred over eight to ten seconds. It is therefore important in the case of sustained forces to take into account not only the force required, but the distance over which the force has to be maintained, as this may significantly impact the cumulative strain placed on the worker.

Effect of load

When considering acceptable load limits for push/pull tasks, it is interesting to note that Snook (1978) specifies acceptable forces for both initial and sustained forces, drawing attention to the fact that sustained forces may play a role in placing workers under excessive physical strain. Mean sustained hand force exertion responses can be seen in Table V.

Table V: Effect of load on average sustained hand forces (N) (SD in brackets).

	Technique		
Load (kg)	Push	1 H Pull	2 H Pull
250	48 (3) ┐	44 (3) ┐	43 (4) ┐
500	116 (8) ┘	102 (6) ┘	104 (7) ┘

└┘ Indicates significant difference ($p<0.05$)

To be expected were the significantly higher hand forces evidenced at the 500kg loads (for all conditions) than at 250kg. The highest of these occurred during pushing, a sustained force of 116N. Differences in the range of 57% to 97% between low and high loads were observed, with the latter occurring during unilateral pulling. Thus in all cases unlike initial forces, doubling the load led to a double, or greater, hand force increase. This increase in hand forces between 250kg and 500kg was significant for all three techniques. Thus while load impacts both initial and sustained forces, the increases detailed in Table V indicate that load may play a more significant role in determining increase in sustained rather than initial forces.

Relatively low standard deviation results are evidenced in the sustained forces (±3 - ±8N). The coefficient of variation for these sustained forces is averaged at 7%, showing that individuals were able to maintain a relatively similar force for the entirety of the sustained phase. The majority of the variance is likely to have occurred as a function of the gait cycle; each step requires acceleration and deceleration of the body, this is translated into the sustained force which is then not a consistently applied force.

Effect of technique

Displaying a trend similar to that observed in initial forces, the average sustained forces demonstrated significant differences between pushing and both of the pulling conditions, with no significant differences between one and two handed pulling; this only occurred at the 500kg load (Figure 11). At the higher load pushing elicited hand forces of magnitudes 14N and 12N higher than one or two handed pulling, increases of 12% and 10% respectively. This suggests that, at higher loads, technique may affect hand forces while at lower loads there does not appear to be a significant influence.

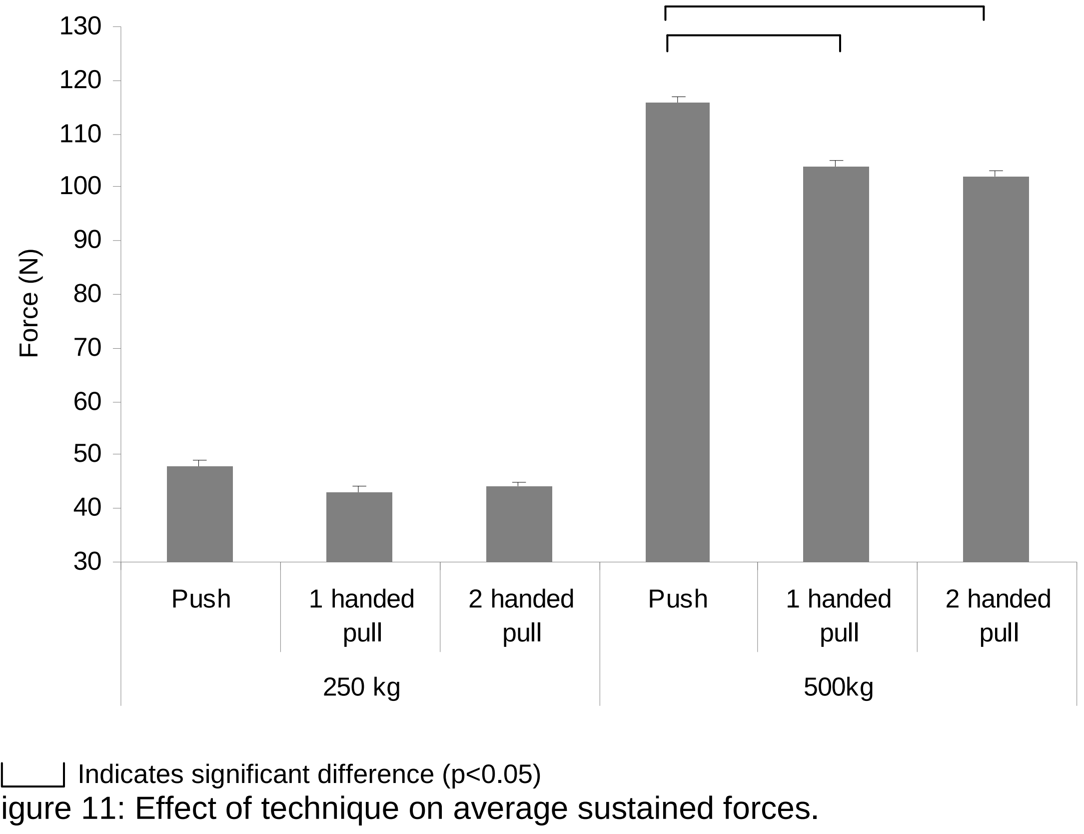


Figure 11: Effect of technique on average sustained forces.

A possible reason for this influence of technique is the position of the load relative to the body; during pushing the load is in front of the body and thus the acceleration inherent in each step is reflected in the higher forces. Coupled with this, during pushing the use of momentum created by the body is negligible when compared to pulling conditions. During pulling the load is behind the body and therefore likely to be less affected by the acceleration/deceleration movements induced by the gait pattern. It is also easier to make use of the momentum created by the body when pulling a wheeled object than it is when pushing. This may account for the lower sustained forces observed during the pulling conditions.

Peak ending forces

Peak ending forces are a function of the load, speed and interaction of environmental factors. As such push/pull literature remains contentious when taking into account the importance of ending forces. Donders **et al.** (1997) found that ending forces were similar to initial forces while Jansen **et al.** (2002) reported significantly lower ending forces. Van der Beek **et al.** (2000) do not indicate significance but report somewhat lower ending forces at different cart weights.

Effect of load

When isolating the effect of load on peak ending forces, results shown in Table VI display a similar trend to initial and sustained forces such that for all three techniques, hand forces were significantly higher at 500kg than at 250kg.

Table VI: Effect of load on peak ending forces (N) (SD in brackets).

	Technique		
Load (kg)	Push	1 H Pull	2 H Pull
250	100 (19)	107 (22)	96 (13)
500	141 (33)	138 (23)	155 (28)

Indicates significant difference ($p<0.05$)

Consistent differences of 30% occurred between 250kg and 500kg, similar to findings within peak initial forces, but much lower than those that occurred in the sustained phase. Thus once again although the load is doubled, this does not related to twicefold increase in hand forces. The highest peak forces occurred during two handed pulling; 107N and 155N for the 250kg and 500kg loads respectively. One handed pulling, similarly to initial and sustained forces, returned the lowest hand force responses at 96N and 138N. Coefficients of variation of 13-21% were relatively low and consistent across the six load/technique combinations. Although the variation described here is low, it is still greater than variation occurring in either initial or sustained force responses.

Effect of technique

As Figure 12 illustrates, no statistically significant differences existed between the three techniques used at either the 250kg or 500kg loads. This is in contrast to the previous initial and sustained force results; in those phases pushing elicited the highest hand forces whilst two handed pulling were of the highest magnitude during this phase. These differences did not however return a significant response.

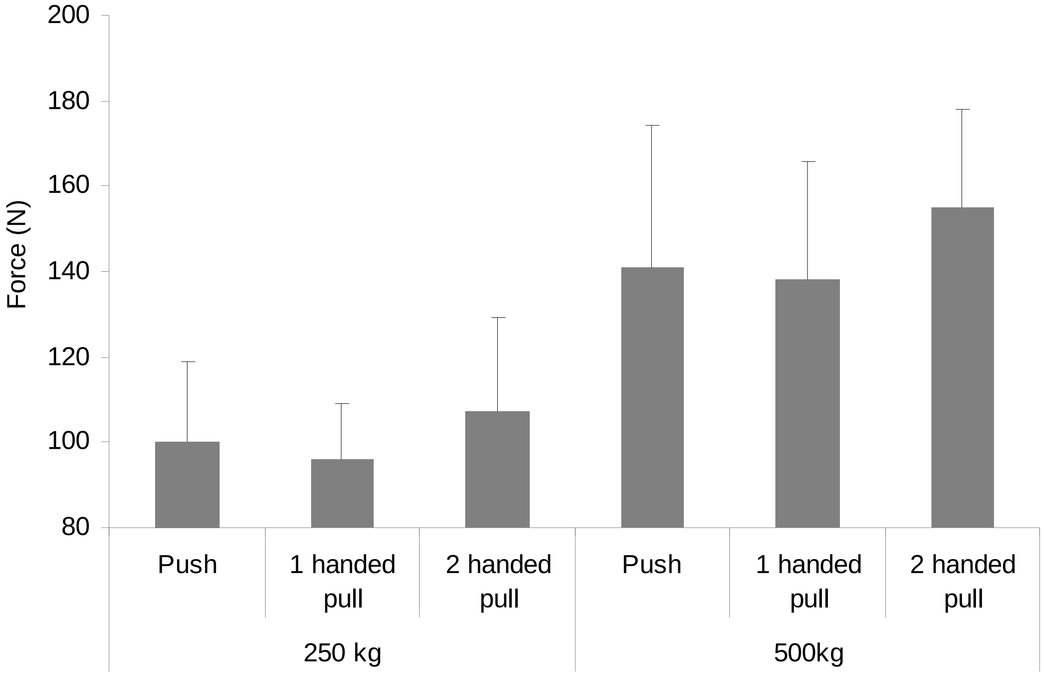


Figure 12: Effect of technique on peak ending forces.

Although the coefficients of variation are low for ending forces (13-21%) these are higher than those evidenced in the initial and sustained phases; this is made explicit by the large standard deviations evidenced in Figure 12. This may in part be due to the jarring technique adopted by some participants, despite comprehensive instructions prior to and during testing. Individuals that used a fast velocity deceleration technique tended to register the highest peak ending forces, indicating that velocity plays a key role in reducing ending forces. In addition participants were counteracting the momentum of the trolley; although this was controlled as rigorously as possible through demarcating of an area at the end of the push/pull distance, there was a certain amount of variation in the speed at which individuals entered this area and terminated the movement. Education of workers may have a role to play in reducing these ending forces; a slow gradual stop reduces peak ending forces and may reduce the cumulative mechanical strain placed on the body significantly over the course of a work shift.

Peak initial, average sustained and peak ending forces

The three acknowledged phases within push/pull movements have elicited investigation from researchers with the aim of determining the phase in which injuries are most likely to occur. The initial phase appears to place human operators under highest physical strain as it evidences the highest hand force requirements (van der Beek **et al.**, 1999; Jansen **et al.**, 2002); nonetheless the research related to this remains somewhat inconclusive. Table VII details significant differences found between exerted hand forces during the various motion phases.

Table VII: Effect of movement phase on hand forces.

Load	Technique	Movement phase	Hand force (N)
250kg	Push	Peak initial	204
		Average sustained	48
		Peak ending	100
	1 H Pull	Peak initial	194
		Average sustained	44
		Peak ending	96
	2 H Pull	Peak initial	202
		Average sustained	44
		Peak ending	107
500kg	Push	Peak initial	333
		Average sustained	116
		Peak ending	141
	1 H Pull	Peak initial	297
		Average sustained	104
		Peak ending	138
	2 H Pull	Peak initial	303
		Average sustained	102
		Peak ending	155

└──┘ Indicates significant difference ($p<0.05$)

Peak initial hand forces were significantly higher than either the sustained or the ending forces, for all push/pull techniques, and at both loads. Initial forces were, on average, 65-75% higher than sustained forces and 50% higher than ending forces. These findings echo those reported previously (Jansen **et al.**, 2002). This would indicate that, in the current study, peak initial forces were placing the greatest amount of physical strain on the individuals' musculoskeletal system due to the magnitude of the force requirement. Peak ending forces were significantly higher than sustained forces for all conditions with the exception of the two handed pull at 500kg, although sustained force (116N) was still 25N lower than the ending force (141N). Table VII illustrates that sustained and ending forces at 500kg are closer in magnitude than at 250kg. It is hypothesised that the load difference is the main influence here; at high loads the load slows down during the ending phase more rapidly due to the increased wheel/floor friction than is evidenced at light loads.

MUSCLE ACTIVATION (ELECTROMYOGRAPHY)

Over the past three decades electromyography (EMG), particularly surface EMG, has evidenced increased application within ergonomic research as it allows access to previously unobservable processes which underlie force production and so affect all human movement (DeLuca, 1993). Basmajian (1974) recommends the use of EMG in gait research, particularly when supplemented with other biomechanical techniques such as high frequency cinematography, accelerometers and foot switches. Within the ergonomic context, EMG has been used as an indicator of fatigue, specifically localized muscular fatigue (LMF), where observable indicators include reduced force production capability, localised discomfort and pain (Redfern, 1992). Redfern (1992) further writes that muscle exertions as low as 10% MVC have shown signs of LMF and thus LMF continues to be of concern in ergonomic assessments. This supports the proposal that understanding muscle activation levels during a task is important in terms of appreciating injury risk. In an effort to be succinct during presentation of the EMG results each muscle will be referred to with an acronym as shown in Table VIII.

Table VIII: Observed muscles with concurrent acronyms.

Specific muscle name (general muscle group)	Acronym
Rectus femoris (Quadriceps)	RF
Biceps femoris (Hamstrings)	BF
Medial gastrocnemius (Calves)	MG
Tibialis Anterior	TA

When reviewing the literature surrounding EMG studies of gait, Basmajian (1974) and Perry (1993) detailed some common muscle activation patterns while acknowledging that discrepancies between individuals remain. While it was outside the scope of the current study to investigate the muscle recruitment patterns within push/pull tasks, it was interesting to note some typical responses to the experimental conditions.

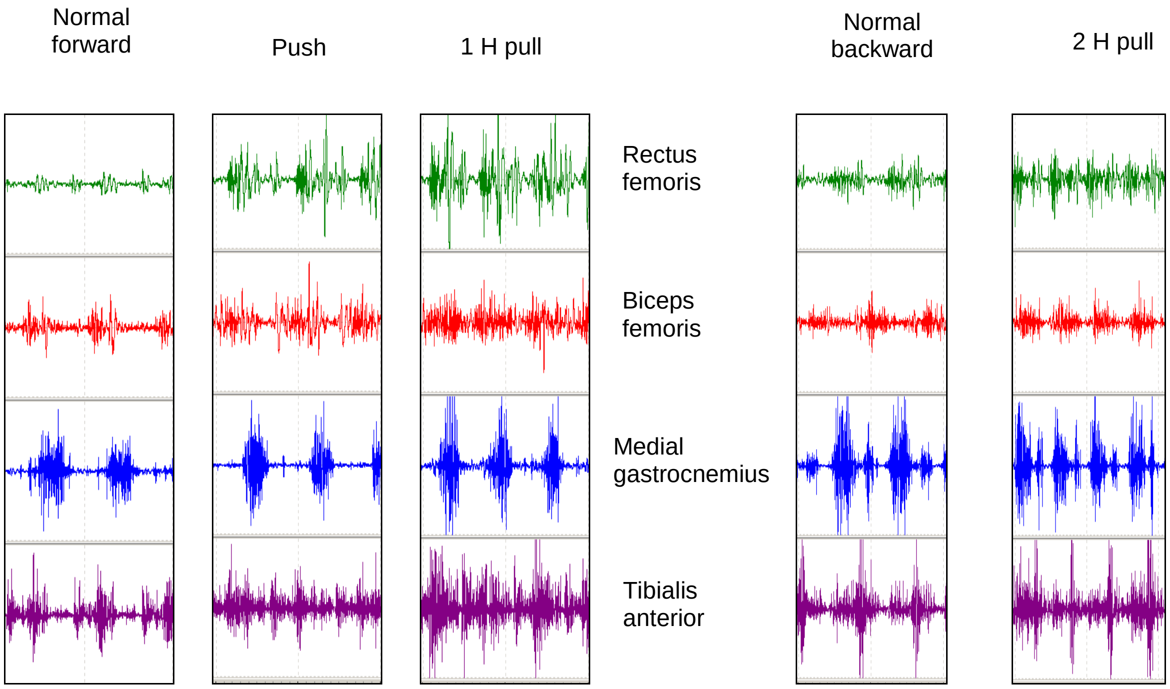


Figure 13: Typical raw EMG tracings from unloaded walking and 500kg push/pull conditions.

A series of three steps from normal walking and the 500kg loaded conditions is shown in Figure 13 as a typical representation of the raw EMG data as it occurred during experimentation. The 500kg loads were chosen to illustrate this, as at this load differences were obvious in all muscles. Additionally, activity was significantly different during the push/pull conditions. Figure 13 illustrates the phasic nature of gait EMG responses in the representatives of the four major muscle groups in the lower limbs. Although no conclusions can be drawn on these typified examples, it serves as an indicator that there is a need for future research in this area to determine not only if there is a difference in magnitude of EMG responses to pushing and pulling, but additionally whether muscle recruitment patterns differ significantly from 'normal' walking.

The current project aimed to assess EMG activity of the lower limbs in order to determine if push/pull technique and/or load had an effect on muscle activity, and furthermore to determine if the muscle activity varied greatly from that observed during normal, unloaded walking. By quantifying the increased muscle activity associated with push/pull tasks, it is the aim to further the understanding of fatigue and injury risk.

Mean lower limb muscle activity

Table IX details the mean muscle activity for the four muscles investigated during the current study, including the two control conditions of normal, unloaded forward and backward walking. This mean muscle activity was derived from the integration of rectified signals.

Table IX: Mean muscle activity as percentage of individual MVC (SD in brackets).

	Condition	RF (%MVC)	BF (%MVC)	MG (%MVC)	TA (%MVC)
	NF	10 (12)	12 (14)	18 (6)	16 (4)
	NB	16 (11)	14 (14)	18 (7)	22 (6)
Push	250kg	12 (12)	12 (12)	21 (7)	17 (4)
	500kg	17 (15)	13 (9)	26 (9)	24 (7)
1 H Pull	250kg	15 (16)	14 (13)	23 (8)	18 (4)
	500kg	22 (19)	17 (14)	29 (12)	26 (8)
2 H Pull	250kg	18 (12)	12 (13)	24 (35)	21 (6)
	500kg	22 (11)	13 (10)	25 (11)	24 (7)

Where NF = normal, unloaded forwards walking; NB = normal, unloaded backwards walking

On average, the lowest activation levels were observed during the normal, unloaded conditions, for all muscles. These were taken as baseline muscle activation levels and compared to those observed during the experimental conditions to quantify the added muscle activity associated with pushing/pulling. The highest muscle activity occurred during one handed pulling of 500kg (29 ±12 %MVC), with pushing eliciting lower muscle activity responses than the pulling techniques at both loads. The differences between the two pulling techniques are not clear as %MVC values are similar at similar loads for these two techniques.

It is evident from the high standard deviations occurring in the EMG responses (between ±4 and ±35 %MVC) that within this sample, as with other EMG research (Lawrence and DeLuca, 1983; Yang and Winter, 1983), there was a substantial amount of inter-individual variation. Grasso **et al.** (1998) reported significant variation between subjects even for the same movement direction, comparable to the current results. Intra-subject variability was consistently lower and for this reason it was imperative that statistical procedures made comparisons within, as opposed to between, individuals for reliable conclusions to be drawn.

Forward and backward walking

The majority of the literature pertaining to muscle activity during backward and forward walking is controversial, accordingly there are few viable conclusions drawn from the research material available (Thorstensson, 1986; Winter **et al.**, 1989; Grasso **et al.,** 1998; Masumoto **et al.** 2007). In the case of the present investigation, forward and backward walking were investigated as control conditions; it was important to determine if an inherent difference in muscle activity between walking directions existed, independent of push/pull conditions.

These results are seen in Table X, where it is clear that three of the four investigated muscles displayed significantly lower muscle activity during forward walking than during backward walking. Differences of 37%, 14% and 27% for RF, BF and TA respectively occur between directions. Medial gastrocnemius displayed no significant differences between gait directions, eliciting an average of 18% MVC in both cases.

Table X: Mean muscle activity during backward and forward walking (SD in brackets).

	Muscle activity (%MVC)			
	RF	BF	MG	TA
Normal unloaded forward	10 (1.2)	12 (1.2)	18 (1.6)	16 (1.5)
Normal unloaded backward	16 (1.2)	14 (1.5)	18 (2.0)	22 (2.1)

Indicates significant difference ($p<0.05$)

These results correspond with those reported by Thorstensson (1986) and Grasso **et al.** (1998) where gait direction was shown to have a significant impact on muscle activity. Grasso **et al**. (1998) detail significantly higher responses to backward walking and conclude that EMG magnitude integrated over a gait cycle is greater during backward walking. These authors reported increases of 220% for RF, 107% for BF, 40% for gastrocnemius and 154% for TA. These increases are substantially higher than those observed in the current study; consideration of walking velocity is however particularly important in this case.

The significantly greater activity responses elicited during backward walking would suggest that in the current sample, independent of pushing and pulling, backward walking induced a higher muscular response than did forward walking. Thus prior to adding any load to the movement directions, backward walking may already be placing workers under greater physical strain than does forward walking. Additionally this is important when considering worker fatigue; increased muscle activity would arguably increase incidence of fatigue and concurrent decrease in endurance time (Rohmert **et al.**, 1986).

The present results indicate that backward walking places an inherent muscular burden on the individual that would then be exacerbated by moving an additional load in the form of backward pulling. This is aligned with the suggestion of Grasso **et al.** (1998) that backward walking is likely to incur a greater level of energy expenditure; greater muscle activation, leading to fatigue is an additional concern, all of which lead to increased muscular demand and physical strain.

Control vs. experimental conditions

As a result of the different walking directions employed during the separate techniques of pushing/pulling, unloaded forward walking was used as a comparison for pushing and one handed pulling while backward walking was the control condition utilised for two handed pulling. It is important to determine the degree to which push/pull manoeuvres affect workers, and to what degree pushing/pulling places them under additional muscular demand; this is possible by comparison against the normal unloaded conditions. Table XI illustrates the presence of statistically significant muscle activity differences between experimental conditions ($p<0.05$) and their respective control conditions.

Table XI: Significant differences between muscle activity: control and experimental conditions.

		Control: Forward walking			
	Load (kg)	RF	BF	MG	TA
Push	250	√		√	
	500	√	√	√	√
1 H Pull	250	√	√	√	√
	500	√	√	√	√
		Control: Backward walking			
		RF	BF	MG	TA
2 H Pull	250	√			
	500	√		√	√

Where √ indicates a significant difference between experimental condition and control

It can be seen that the majority of the muscle activity evidenced during experimental conditions was significantly higher than that experienced during unloaded walking. During forward walking conditions, only two responses were not significant (p =0.13 and 0.96 respectively), those of the BF and TA during two handed pushing at the lighter load. Regardless of the load moved, muscle activity during one handed pulling was significantly higher (p = 0.001) than the control condition indicating that additional muscular demand may be highest in these conditions. At 250kg, two handed pulling only elicited a significant response in the RF muscle while at 500kg, three out of four muscle responses were significantly higher (p = 0.0001) than unloaded backward walking. At the lower loads, pushing and two handed pulling involved the least additional muscular effort as compared to unloaded walking; at the heavier load, all three techniques required statistically significantly additional muscular demands to elicit load movement.

Experimental conditions

Effect of load

Information regarding muscle activity of the lower limbs during pushing/pulling is, as yet, not available in the literature, thus it was not clear what responses would be observed in the current study. Results regarding muscle activity are displayed in Figure 14. In each case the mean results from the 250kg and the 500kg loads are connected to illustrate the gradient of the slope representing the rate of increase in muscle activation between the loads. Relatively few load dependent significant differences occurred within muscle activity responses; RF and BF showed no load effects for any of the three techniques. MG responses demonstrated significantly higher muscle activity at 500kg during two handed pulling whilst TA muscle activity was statistically significant during pushing and one handed pulling.

Increases between low and high loads ranged from 7% to 37%, with the highest increase occurring in the TA muscle during one handed pulling. At lighter loads pushing elicited the lowest muscle activity responses in all four muscles. Conversely two handed pulling evoked the highest muscle activity in three of the four muscles (RF, MG, TA) thus could be considered the most physically demanding technique at this load. Conversely, at the heavier load pushing was only best in two of four muscles (RF, BF) while one handed pulling was worst in three of the four muscles (BF, MG, TA). Consequently at 500kg loads, when regarding lower limb muscle activity, one handed pulling was possibly the most demanding technique whilst the advantage between pushing and two handed pulling is not clear. These results suggest that, unlike hand forces, the majority of the muscles observed in the current study were not significantly impacted by load increases from 250kg to 500kg. More comprehensive insights into these results may be gained through investigation of muscular activity in the upper body. It may be that there are greater postural adjustments in the upper body at higher loads, allowing for greater hand force production without necessarily increasing muscle recruitment in the lower limbs. This highlights the need for future integrated research regarding muscle activity of both the upper and lower body during pushing and pulling.

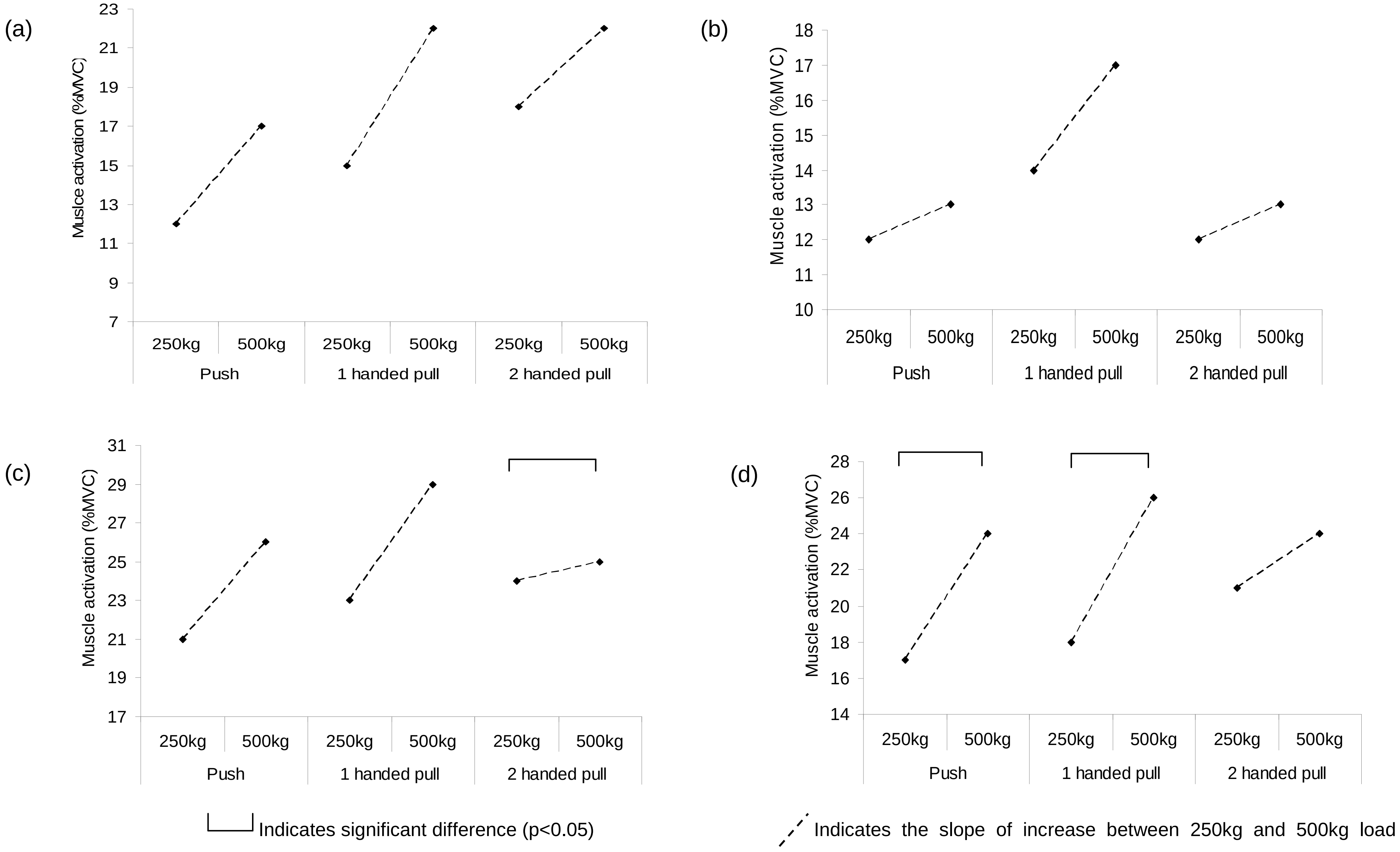


Figure 14: Effect of load on muscle activation of (a) Rectus femoris (b) Biceps femoris, (c) Medial gastrocnemius, (d) Tibialis anterior.

Effect of technique

When the percentage increases between the lighter and heavier loads (shown by the slope of the lines connecting the mean values in Figure 14) are averaged across all four muscles, increases of 21%, 24% and 14% occurred during pushing, one handed pulling and two handed pulling respectively. These increases reflect that responses to load are greater in pushing and one handed pulling than in two handed pulling. Consequently although the responses for two handed pulling are generally higher than the other techniques, it is not as greatly affected by increases in load. The shallow gradients evidenced in two handed pulling clearly illustrate that muscle activity responses during this technique increases to a lesser extent with increasing load than it does during pushing or one handed pulling.

Table XII: Effect of technique on lower limb muscle activity responses (SD in brackets).

		Muscle activity (%MVC)			
Load	Technique	RF	BF	MG	TA
250kg	Push	12 (12)	12 (12)	21 (7)	17 (4)
	1 handed pull	15 (16)	14 (13)	23 (8)	18 (4)
	2 handed pull	18 (12)	12 (13)	24 (35)	21 (6)
500kg	Push	17 (15)	13 (9)	26 (9)	24 (7)
	1 handed pull	22 (19)	17 (14)	29 (12)	26 (8)
	2 handed pull	22 (11)	13 (10)	25 (11)	24 (7)

Indicates significant difference (p<0.05)

At the 250kg load, the technique eliciting lowest responses in three of the four muscles (RF, BF and TA) was pushing (Table XII). Differences at the 250kg load display similar trends for the RF and TA muscles: pushing elicits the lowest responses, one handed the next highest and two handed pulling the highest responses. However these differences are only statistically significant between pushing and two handed pulling. BF and MG display no statistically significant technique effects at 250kg. These results tenuously indicate that at 250kg, technique may play a role in lower limb muscle activity responses, and it is suggested that at this load pushing is the technique likely to place the least strain on the worker. At lower loads, while pushing appears to be preferable, if this technique cannot be employed it is not clear that there is any advantage utilising either of the pulling techniques above the other. It is interesting, however, to note that Li **et al**. (2008) report that one handed pulling only occurs at lower loads as high loads exceed one handed pulling capacity.

No statistically significant technique effects were present at 500kg. Although one handed pulling elicited the highest muscle activity, this was not statistically higher than the other techniques. The high standard deviations evidenced in the current EMG results may explain the lack of significant muscle activity differences between techniques. Basmajian (1974) reports a high variation in individual muscle recruitment patterns and Goebel (2005) advises that reliability of direct EMG measures is low as a result of differences in muscle geometry, electrode location and subcutaneous tissue although this is increased if electrodes are not replaced during testing. Additionally as suggested by Lawrence and DeLuca (1983) and Yang and Winter (1983), high inter-subject variability is common in EMG studies. This makes comparison between individuals more difficult and is posed as a possible reason for the lack of expected significant differences in muscle activity.

In summary, technique effects are likely to be load dependant; at 250kg pushing is advantageous over the two pulling techniques, but this advantage does not appear to occur at higher loads. However, in general, pushing elicits lower muscle activity than pulling whilst two handed pulling is the technique least affected by increases in load from 250kg to 500kg. The high inter-individual differences evidenced are likely to influence the presence of significant differences between load and technique changes.

GAIT RESPONSES

An aim of the current study was to investigate the gait patterns occurring during pushing/pulling; this was accomplished using both basic and complex measures. Li **et al.** (2008) report that load differences had a significant effect on walking speed while pushing/pulling; as authors have acknowledged (Winter, 1991;

Stoquart **et al.**, 2008), walking velocity influences gait patterns. This supports the actions of the current investigation to control walking speed; in this way differences are more reliably due to load/technique factors as opposed to being affected by speed changes.

In order to determine the phases of the gait cycle, specific sequences of footswitches were monitored, based on Figure 3 (page 25) and Figure 6 (page 45). Specific phases were measured using the sensors placement as follows:

Stride length – right heel to right heel
Foot contact – heel to toe
Breaking double support – heel strike of one foot to toe off of opposite foot
Thrusting double support – heel strike of opposite foot to toe off
Single support – toe off to heel strike of opposite foot

Stride length and cadence

Basic gait measures were taken using direct observation, advocated by Perry (1992). This was to determine if the basic parameters of stride length and cadence were affected by the load/technique combinations during dynamic pushing/pulling. A distance of 7m was used when investigating gait patterns for the current study, with the velocity strictly controlled using a series of light emitting diodes (LEDs). The number of steps were manually counted and the number of strides (and thus cadence) were then calculated based on this.

Table XIII: Mean number of strides (over 7m) and stride length results (SD in brackets).

	Condition	Number of strides	Mean stride length (m)
	NF	5.0 (0.7)	1.4
	NB	6.0 (0.9)	1.1
Push	250kg	5.0 (0.7)	1.4
	500kg	5.0 (1.0)	1.4
1 handed pull	250kg	5.0 (0.7)	1.4
	500kg	6.0 (1.2)	1.1
2 handed pull	250kg	6.0 (1.2)	1.1
	500kg	7.0 (1.2)	1.0

Where NF = normal, unloaded forward walking; NB = normal, unloaded backward walking

Table XIII details the average number of strides taken over the 7m distance and the mean stride length for the control and experimental conditions. The number of strides taken was consistent across the conditions, with marginally more steps being performed during backward walking. Table XIII further illustrates the relationship between number of strides and stride length; a decrease in stride length causes a concurrent increase in number of steps taken to cover the same distance. With regards to one and two handed pulling, at 500kg there is an increase in the number of strides taken when compared to the 250kg load. One and two handed pulling at 250kg evidenced stride lengths on average 0.3m and 0.1m higher than those evidenced at 500kg. These differences are not statistically significant, however they do echo responses reported by Li **et al.** (2008) where stride lengths at low loads were significantly higher than those at medium and high loads (0.82m, 0.73m and 0.63m for low, medium and high loads).

In order to calculate cadence, the formula of *Cadence (steps.min*$^{-1}$*) = steps counted x 60/time (s)* was used. An average cadence of 78 steps.min $^{-1}$ was recorded, when considering all control and experimental conditions. This is much lower than the male average cadence of 111 steps.min^{-1} as reported by Perry in 1992. The velocities adhered to in the current study are however much lower than normal walking velocity, and are in fact classified as ‘slow’ by Charteris (1982). This velocity was appropriate for the task in terms of moving the heavy 500kg load; however it makes comparison to values obtained during ‘normal’ walking (generally higher velocities) difficult.

Stride duration

A variety of measures were collected utilising the Tekscan FlexiForce A201 Variable Resistance Sensors, using methods and sensor placements that are commonly evidenced within gait research (Wall **et al.**, 1977; Perry, 1992). Most gait results were calculated as percentages of a gait cycle, as shown in Figure 3 (page 25), and only the strides taken during the sustained phase of the push/pull were utilised for analysis. This negated the possibility that the gait cycles would be affected by starting/stopping.

Effect of load and technique

The stride duration (taken from right heel strike to subsequent right heel strike) was measured in seconds to determine how much absolute time individuals spent in each stride.

Table XIV: Average stride durations (seconds (s)) for control and experimental conditions.

	Condition	Mean (SD)
	NF	1.43 (0.08)
	NB	1.40 (0.10)
Push	250kg	1.47 (0.12)
	500kg	1.47 (0.13)
1 handed pull	250kg	1.41 (0.11)
	500kg	1.37 (0.15)
2 handed pull	250kg	1.38 (0.13)
	500kg	1.44 (0.19)

└─┘ Indicates significant difference ($p<0.05$). NF = normal, unloaded forward walking, NB = normal, unloaded backward walking

Regarding Table XIV, it is important to note that stride duration times varied, on average, 0.09s between longest and shortest stride times, with low variation within each condition (average coefficient of variation being 9%). Normal unloaded backward walking stride duration was shorter than that of normal unloaded forwards walking, however this difference was not statistically significant. This slight decrease in stride time when walking backwards corresponds to the numbers of strides taken (Table XIII) such that during backward walking, strides are slightly shorter in duration, this is then offset by a higher cadence.

When considering differences from ‘normal’ walking, no statistically significant responses were found. Pushing at both loads evoked stride durations of 1.47s, greater than that of normal forward walking (1.43s), however this was not statistically significant. However when pushing loads of up to 500kg, individuals spend longer on each stride than occurs when walking unloaded. This may be a result of the postures adopted during pushing whereby individuals lean forward slightly (Figure 15), altering their centre of balance and using the trolley handle for support, enabling individuals to take slightly longer strides than they would during normal upright walking. When one considers the effect of load and technique on stride duration, it can be said that, statistically, there is no difference between the six technique/load combinations.

Figure 15: Examples of forward and backward leaning during pushing, one handed pulling and two handed pulling.

Foot contact times

The foot contact times utilised in the current study correspond with the stance phase as seen in Figure 3 (page 25) of the gait cycle. In the case of forward walking conditions this occurs from heel to toe contact, conversely during backward walking the contact was reversed (toe to heel contact). All percentages are given relative to one gait cycle (right heel strike-right heel strike).

Table XV: Right and left foot contact times (SD in brackets).

	Condition	Foot contact % (Right)	Foot contact % (Left)
	NF	75 (4.3)	74 (4.4)
	NB	72 (5.2)	70 (4.4)
Push	250kg	74 (5.6)	75 (4.8)
	500kg	75 (9.1)	74 (6.1)
1 handed pull	250kg	76 (8.4)	74 (6.3)
	500kg	73 (9.3)	73 (7.1)
2 handed pull	250kg	73 (8.5)	72 (7.2)
	500kg	72 (9.8)	70 (8.2)

Indicates significant difference ($p<0.05$). NF = normal forward walking, NB = normal backward walking

Table XV details the right and left foot contact times when considered as a percentage of the gait cycle (one stride). Contact times are relatively high, between 70% and 76%; however variation within the conditions is low (between 5% and 14% variance on the right foot and 6% and 12% variance on the left foot). It is interesting to note that foot contact between forward and backward walking were only significantly different in the left foot, whereby the left foot spent 5% less time in contact with the ground during backward walking. Similarly the right foot displayed this trend, however there is only 4% lower contact during backward walking, which does not return a statistically significant result. Foot contact during unloaded forward and backward walking was found to be significantly different in the left but not right foot contact (70% & 74% and 72% & 75% respectively). Despite the lack of statistical significance in these results, in both cases contact time was lower during backward walking.

Effect of load and technique

Neither load differences nor technique appeared to influence foot contact responses; no statistically significant results were observed between light and heavy loads for any of the three push/pull techniques. Right foot contact displayed no significant differences between techniques, with the greatest difference at both loads only amounting to 3%. Left foot contact responses between techniques remained similar, resulting in a 3% and 4% difference during 250kg and 500kg conditions. These results would suggest that neither load nor technique has a significant impact on foot contact patterns during pushing/pulling, and that statistically, these are no different to normal unloaded walking.

Double and single support

The stance phase is typically divided into double (DS) and single support (SS) phases, depending on whether the contralateral leg is in the stance or swing phase. The body is most stable when in DS and least stable in SS (Perry, 1992). Within DS, there are two sub-categories, braking double support (BDS) which occurs in conjunction with heel strike, and thrusting double support (TDS) which occurs in conjunction with toe-off (see Figure 3, page 25). No statistically significant difference occurred between BDS and TDS, which aligns with the trends displayed during normal walking. Table XVI illustrates results for all DS and SS contact times (as a percentage of the stance phase).

During normal walking conditions it can be seen that in the case of both BDS and TDS, contact times during backward walking were lower than during forward walking, a difference of 1% and 3% for BDS and TDS respectively. Only the difference in TDS is statistically significant.

Table XVI: Braking and thrusting double support (DS) and single support (SS) (SD in brackets) as a percentage of stance phase.

	Condition	Braking DS	Thrusting DS	SS Right	SS Left
	NF	26 (8.7)	25 (4.2)	30 (13.5)	25 (4.3)
	NB	25 (14.0)	22 (5.3)	31 (6.2)	27 (5.2)
Push	250kg	26 (7.3)	25 (6.5)	27 (5.7)	26 (5.6)
	500kg	25 (10.1)	24 (7.8)	33 (16.8)	25 (6.7)
1 handed pull	250kg	28 (12.0)	26 (7.3)	31 (11.7)	25 (6.3)
	500kg	26 (12.8)	25 (7.0)	29 (7.5)	27 (6.8)
2 handed pull	250kg	25 (11.0)	25 (7.8)	29 (7.9)	27 (7.5)
	500kg	30 (12.0)	24 (5.4)	34 (13.6)	28 (7.1)

Indicates significant difference (p<0.05). NF = normal forward walking, NB = normal backward walking

BDS responses show that the highest contact time occurred during two handed pulling of a 500kg load (30%), while TDS responses are more mixed, with the greatest time spent in TDS during one handed pulling (26%). When experimental conditions are compared to the control conditions, no significant differences were found.

SS contact times vary between 25% and 34%, with no statistically significant differences occurring between unloaded forward and backward walking on either foot. During SS, when pushing/pulling conditions are compared to the control conditions, it can be seen that SS values are not significantly different, suggesting that individuals were not significantly more or less stable during the push/pull conditions than they were during normal walking.

Effect of load and technique

Statistically, there is no significant impact of either load or technique on TDS, BDS or SS possibly as a result of the high standard deviations evidenced in Table XVI. Although it was expected that individuals would spend more time in DS during the push/pull conditions as a result of the need to provide balance, it is possible that individuals were using the trolley handle for a degree of support. Li **et al.** (2008) indicate that the handle is a key component of reducing the risk of trauma to workers during a ST&F accident; although the trolley is moving, there is a small measure of support provided by the pallet jack handle.

Gait responses to pushing/pulling have yet to be fully investigated within the literature, further research is essential in ensuring valid and reliable information regarding gait pattern modification during push/pull tasks. The responses detailed in the current study suggest that, in general, there are few differences in gait patterns between normal unloaded walking and pushing/pulling conditions. However this field of knowledge would be greatly enhanced by including kinematic and kinetic evaluations alongside lower limb muscle activity observation during push/pull tasks.

BODY DISCOMFORT

The body discomfort map developed by Corlett and Bishop (1976) has been adapted for use in various settings to allow for a perceptual measure of task demands; in addition to this it can provide an important indicator of potential musculoskeletal problems. Participants were allowed to rate up to three regions of body discomfort per condition but were not forced to rate areas if they felt that it was not necessary. Intensity ratings (1-10) for each region were also given; this compiled data is displayed in Table XVII.

Table XVII: Body discomfort perception with number of ratings and (mean intensity).

		Body region						
	Condition	Shoulders	Biceps	Forearm	Wrist	Quadriceps	Calves	Lower back
250 kg	Push		1 (2)		1 (1)		3 (2)	
	1 H pull	4 (3)	3 (2)	1 (1)		1 (2)	5 (2)	
	2 H pull					1 (3)	3 (4)	1 (1)
500 kg	Push		3 (3)	2 (2)	2 (2)	1 (2)	7 (3)	
	1 H pull	7 (3)	5 (2)	2 (3)	2 (2)		5 (3)	2 (4)
	2 H pull	6 (3)	4 (2)				19 (3)	2 (4)

This data shows a strong perception of discomfort in the calves (42 ratings; average discomfort intensity of 3/10); the highest number of ratings was given during two handed pulling at 500kg. The biceps received 16 ratings, with a discomfort intensity of 2, the most discomfort occurring during one handed pulling. In the case of one handed pulling, discomfort was rated only on the right side (dominant hand being used to pull) in the upper body (biceps and shoulder), highlighting the impact of the asymmetrical nature of forward pulling on the musculoskeletal system. Of additional concern were the shoulders, with 17 ratings, average intensity of 3. Once again this was highest in two handed pulling (500kg).

Effect of load and technique

As would be expected, at higher loads greater numbers of discomfort ratings occurred, suggesting that higher loads are likely to elicit increased discomfort; an important finding when combined with biomechanical responses detailed previously. When considering technique, it is obvious that the most discomfort in the upper body was felt during one handed pulling, particularly at the heavier load. The lower body discomfort suggests that two handed pulling is least preferable as at both loads it received the highest and most intense discomfort ratings, particularly at the 500kg load. In general pushing evoked the least discomfort in both the upper and lower extremities, indicating that this technique was subjectively rated as the one in which the least discomfort was experienced.

While these perceptual data are by nature subjective, it does indicate that participants felt the calves, biceps and shoulders to be most taxed by the push/pull conditions. This is in agreement with the findings of Cripwell (2007) who argues that repetitive pushing/pulling may increase the risk of lower limb injuries. In the current study the concern lay mostly in the lower body, but it is acknowledged that investigation into upper body musculoskeletal responses would be integral to understanding the demands placed on the body by pushing/pulling. Furthermore these findings clearly show that dynamic push/pull exertions require whole body involvement; both upper and lower body as well as anterior and posterior portions of the body evidenced discomfort. Interestingly none of the body discomfort intensity ratings were higher than 4/10, suggesting that while there were areas of discomfort, these were mild; this is partly due to the stop/start nature of the experimentation as individuals were only exerting force for 10-15 seconds. Thus the current results may only be comparable to infrequent exertions at the specified loads.

CHAPTER V

DISCUSSION

INTRODUCTION

Ergonomics as a profession strives to reduce incidents of injury and fatigue within the workplace as a means of improving worker well being and productivity; a twofold objective that benefits both employees and employers. Through better understanding of the physical and psychophysical demands placed on workers, particularly in manual intensive tasks such as pushing and pulling, Ergonomists can aid in designing tasks such that they are less likely to result in overexertion injuries induced by excessive task demands (Dempsey, 1998). Concurrently this aids in improving worker productivity by ensuring that individuals perform as efficiently as possible. The current study endeavoured to quantify biomechanical and psychophysical demands to varying task demands during various push/pull techniques in order to further understanding in this essential field of ergonomic research.

HAND FORCE EXERTION

Risk evaluation of pushing/pulling tasks commonly involves assessment of exerted hand forces (Hoozemans **et al.**, 1998; van der Beek **et al.**, 1999) as it is expected that an increase in these hand forces is accompanied by an increase in mechanical loading on the musculoskeletal system (Jansen **et al.**, 2002). The majority of push/pull research has concentrated on hand force exertion and many of the guidelines regarding acceptable task limits have been set using the basis of force exertion (Snook, 1978; Snook and Ciriello, 1991; van der Beek **et al.**, 1999). Although Van der Beek **et al.** (1999) suggest that resultant hand forces usually have a vertical component, push/pull research has tended to consider horizontal forces as these are seen to be representative of the force exertion. This supports the assertion by Hoozmans **et al.** (1998) that pushing/pulling primarily involve horizontal hand forces. These informed the current study where only horizontal hand forces were considered.

Motion phases

Of the hand force responses observed, those elicited during the initial phase were of magnitudes 65-75% higher than sustained forces and 50% higher than ending forces. These results support earlier findings (Donders **et al.**, 1997; Jansen **et al.**, 2002) and indicate that initial forces place the greatest physical strain on the musculoskeletal system. Numerous studies have reported initial forces of significantly higher magnitudes than sustained forces (Donders **et al.**, 1997; van der Beek **et al.**, 2000; Jansen **et al.**, 2002) while differences between initial and ending forces remain inconclusive (Donders **et al.**, 1997; Jansen **et al.**, 2002). It is expected that initial forces are likely to be highest, both inertia and wheel-floor friction have to be overcome to initiate movement.

Load mass had a significant effect on hand forces exerted in all three motion phases ($p<0.05$). This conclusion was expected as an increase in load mass requires a subsequent increase in the force required to move it. Interestingly this relationship between force exertion and load mass was not the same for the three phases. In the initial and ending phases, a twofold increase in load resulted in a 31-38% increase in hand force, however a doubled load led to a 57-97% increase in sustained forces. This illustrates the fact that load appears to have a stronger impact on sustained forces. These findings are similar to those evidenced in the literature; a 150kg increase in load mass (for both pushing and pulling) increased initial, sustained and ending forces 15%, 33% and 13% respectively (Donders **et al.**, 1997). Correspondingly van der Beek **et al.** (2000) evidenced increases of 29%, 43% and 40% in the three motion phases with an approximately doubled load. Thus results indicate that load increases have the greatest impact on the sustained forces, implying the importance of considering this motion phase in future studies. These findings may be explained with regards to rolling friction; when load increases, the resulting added rolling friction means that it becomes more difficult to keep moving.

When considering the effect of technique on forces exerted in the motion phases, initial and sustained phases revealed similar trends. At the 500kg load, pushing elicited higher hand forces than did one or two handed pulling conditions (7-9%

and 10-12% higher initial and sustained forces respectively). No statistically significant differences were found between the techniques during the ending phase at either load. This disparity between techniques may in part be explained by the placement of the load relative to the body; during pulling the load is behind the body and individuals are able to make use of the momentum created by both the forward movement and the body posture. During pushing the hand forces are likely to be greatly affected by the acceleration/deceleration caused by the gait cycle, particularly during sustained movement.

Few investigations within the literature allow for comparison with regards to technique effects on hand forces. Donders **et al.** (1997) compared pushing and pulling (two handed) at loads of 130kg, 250kg and 400kg. These authors found initial forces of magnitudes 14-27% higher in pushing than pulling. Sustained forces were more consistent between the two with pushing eliciting 2-16% higher hand forces than pulling. Conversely ending forces results show pulling evoked forces of between 5 % and 8% greater than pushing. Results from a study by van der Beek **et al.** (2000) are slightly more contradictory as pulling elicited 4-16% higher hand forces than pushing, particularly at higher loads. However the trend in lower loads is similar whereby pushing elicited highest initial and sustained forces. Current results show no technique effect for ending hand forces whilst Donders **et al.** (1997) and van der Beek **et al.** (2000) report slightly higher forces during pulling. When regarding push/pull technique on specific motion phase hand forces, it appears that pushing elicits higher hand forces than pulling in the initial and sustained phases, however the impact of technique on ending forces remains inconclusive.

Peak initial hand force exertion

Detailed examination of the initial hand force responses revealed a number of important discussion points, particularly with reference to the influence of load. Several studies within push/pull literature have examined the effect of load on peak initial forces, predominately during dynamic pushing. This research indicates that load is a foremost factor in the development of forces during pushing and pulling (Jung **et al.**, 2005). Results from the current investigation indicated that factors other than load mass were likely to be important in determining these hand forces; further discussion illustrates these additional influencing factors. Table XVIII compares the initial forces recorded in the current study to those evidenced at similar (although often not identical) loads within analogous studies. Although many authors within this research do not specify whether hand forces collected were horizontal, of those that do, collection of hand force data in the horizontal plane only is by far the most common.

Table XVIII: Initial hand force requirements at similar loads for pushing.

Author	Load (kg)	Initial hand force (N)
Resnick and Chaffin (1995)	225	300
Donders **et al.** (1997)	250	190
Van der Beek **et al.** (2000)	250	361
Current study	250	204
Resnick and Chaffin (1995)	450	470
Donders **et al.** (1997)	400	320
Van der Beek **et al.** (2000)	550	456
Current study	500	333

Table XVIII illustrates the variation evidenced in peak initial forces across studies, even when at similar loads. As an example, at 250kg, two studies (Donders **et al.**, 1997; van der Beek **et al.**, 2000) elicited a range of 171N for initial forces; results from the current project occurred within this range at 204N. At the 500kg load, there are no directly comparable studies; however the trends are similar, with a wide range of forces derived from similar loads. This comparison is particularly interesting when considered in conjunction with Figure 16, which illustrates the relationship found between load and initial forces from various authors (Resnick and Chaffin, 1995; Donders **et al.**, 1997; van der Beek **et al.**, 2000). For all of the studies concerned, a linear relationship between peak initial exerted forces and load existed; R^2 values of between 0.89 and 0.98 indicate that the correlations between these variables are very strong.

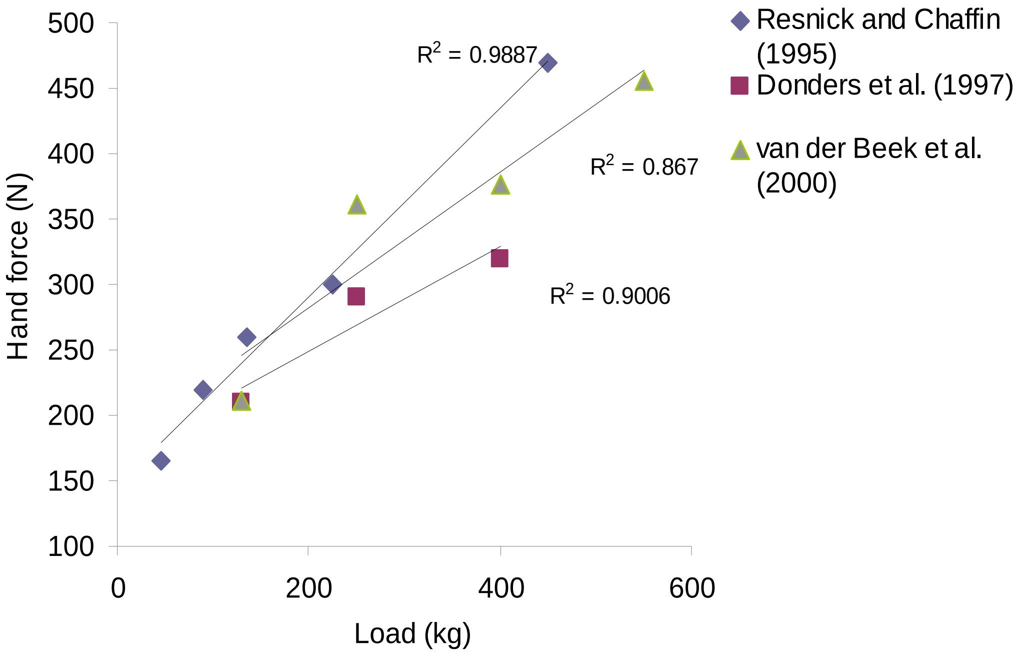


Figure 16: Linear relationship between load and peak initial forces.

Despite these correlations, it is important to consider the fact that although the relationships are linear, they are not identical; this is obvious from the variation in slope of the lines in Figure 16, and from the range of initial forces evidenced at similar loads in different studies (Table XVIII). While these results concur that an increase in load leads to an increase in hand force, it appears that each situation is unique. Initial peak forces are arguably a function of load/floor interaction (at the floor/wheel interface) rather than technique. This factor is constant during all push/pull conditions and at the different loads and thus initial hand force is mostly dependant on frictional forces being overcome. Thus it is the frictional force that may play the most important role, above technique, in determining the magnitude of hand forces required to overcome inertia and start the pallet jack moving.

The outcomes shown in Figure 16 were taken from ‘ideal case’ scenarios where conditions were rigorously controlled, in industry these ideal situations are highly unlikely. Considering the difference in environmental factors, particularly flooring, wheel-floor friction and trolley maintenance, that can occur within industry it appears that each case must be considered individually, and that hand forces incurred in one situation are not applicable to circumstances elsewhere. These findings emphasise that hand forces are determined by more than the load and cognisance must be paid to a holistic consideration of the host of influencing factors detailed by Mack **et al.** (1995) and Jung **et al.** (2005). The linear relationship does make it possible to extrapolate required hand force exertion from relatively low loads to higher ones, if the specific linear relationship is discovered. This is important as it allows Ergonomists to test relatively low loads, thus less likely to result in injury, and extrapolate the findings. In this way acceptable hand force limits can be determined without placing the workers involved at undue risk of injury. Cognisance of the fact that each situation needs to be considered in isolation is important; the host of environmental factors affecting these initial forces are complex and varied between industries and work places.

Acceptability of hand force exertion

For over three decades, researchers have attempted to set ‘acceptable’ guidelines, the first of these being those developed by Snook (1978) and Snook and Ciriello (1991) using psychophysical methodology. However these authors emphasised that several assumptions were made during guideline formation; not every value is based on experimental results. Furthermore a recent publication suggested that secular changes have led to a 6-18% decrease in maximum acceptable weights in push/pull tasks (Ciriello **et al.**, 2008), highlighting the importance of constant re-evaluation of these parameters. Nevertheless the guidelines have been extensively used within industry to inform push/pull task designs. Further guidelines and acceptable limits have been set by various authors, utilising predominately biomechanical and psychophysical measures. These have been summarised in Table XIX.

Table XIX: Summary of acceptable limits set for push/pull tasks.

Author	Recommended acceptable limit	Details
Snook (1978)	Push = 373N	30.5m, handle height 0.95m, one push per 8 hours
Eastman Kodak (1986)	Initial = 225N Sustained = 112N	No details provided
Snook and Ciriello (1991)	Push = 471N Pull = 412N	7.6m, handle height 0.95m, one push per 8 hours
Resnick and Chaffin (1995)	225 kg (trolley load)	No details provided
Van der Beek **et al.** (2000)	Initial = less than 304N	Less than 250kg load limit
Ciriello **et al.** (2001)	Initial = 403N Sustained 221N	Amounts to 482kg for a 13s push
Haslam **et al.** (2002)	Push = 439 N Pull 430N	No details provided
Ciriello (2004)	Initial 247-272 N Sustained 153-165N	374kg load limit
Ferreira (2004)	245N	No details provided
Jung **et al.** (2005)	225N	No details provided

The hand forces observed in the current study are generally lower than the limits recommended by the authors in Table XIX. Using these guidelines, Table XX then further illustrates which of the hand forces observed in the current would be acceptable. To determine acceptability of the current results, use was made of the most conservative estimates from Table XIX, that of Eastman Kodak (1986). As Table XIX illustrates, estimates of acceptability are contradictory, however from an injury prevention standpoint it is prudent to utilise the guidelines that afford greatest protection to workers; those recommended by Eastman Kodak (1986) fulfil this requirement.

Table XX: Hand forces from the current study, illustrating acceptability.

		Peak initial (N)	Sustained (N)	Peak ending (N)
250kg	Push	**204**	**48**	***100***
	2 Pull	**202**	**44**	***107***
	1 Pull	**194**	**43**	***96***
500kg	Push	**333**	**116**	***141***
	2 Pull	**303**	**102**	***155***
	1 Pull	**297**	**104**	***138***

Figures in **red** indicate not acceptable by the most conservative guideline, and **green** indicates acceptable by the same guideline. ***Italics*** indicate conditions for which no guidelines currently exist.

Of the current hand force results, initial forces at 500kg were considered potentially injurious, suggesting that this may be an area of concern. Sustained forces were within acceptable guidelines, with the exception of pushing (500kg) where the resulting force was unacceptable according to Eastman Kodak (1986). Unfortunately there are no studies as yet indicating acceptable ending forces thus these have no comparison.

As is shown, guidelines regarding acceptable limits for pushing/pulling are inconsistent. Haslam **et al.** (2002) propose that variation amongst similar push/pull studies may arise from methodological differences such as trolley loading and force assessment techniques. Furthermore differences in apparatus and procedures have a strong influence when the psychophysical method is applied; this may account for the range of 'acceptable' hand forces recommended within the literature.

It is also important to note at this juncture that factors such as distance and frequency of push/pulls will significantly impact the 'acceptable' forces. Increased distance or frequency of push/pull task has the effect of lowering the acceptable load or hand force exertion, particularly if task duration also increases. Eastman Kodak (1986) recommends that manual vehicles should be used fewer than 25 times per hour. Ferreira **et al.** (2004) recommend adequate opportunity to rest and recover if tasks are frequently repetitive. Additionally the function of frequency and distance is dependent on the speed at which the task is performed; Jung **et al.**

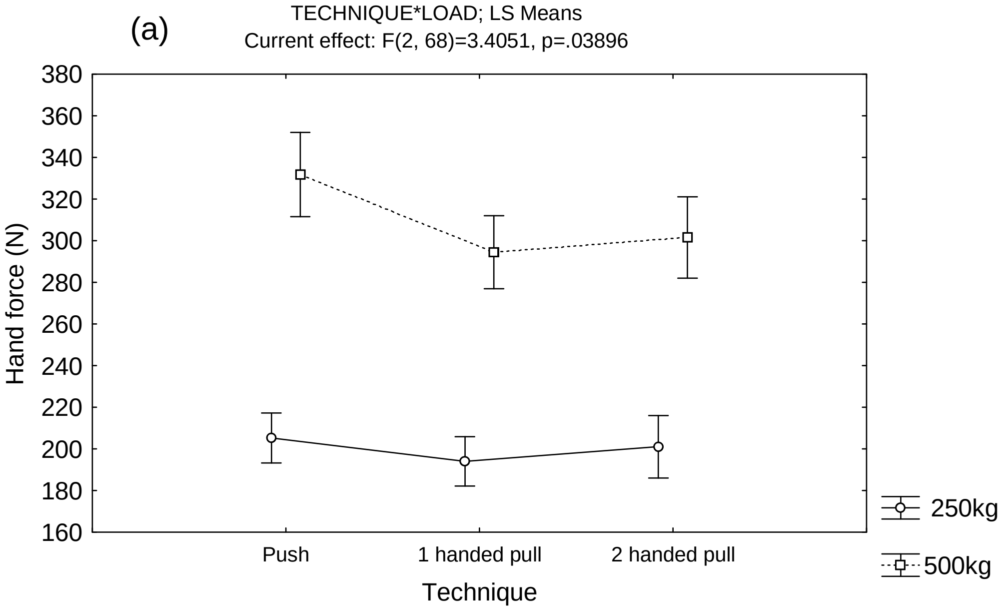
(2005) reiterate this when suggesting that the greater the speed of handling, the greater the physical stress on the operator.

Buckle **et al.** (1992) caution the use of general guidelines, suggesting that indiscriminate use could lead to serious implications in the workplace. With specific reference to push/pull limits, these authors assert that factors such as handle height, foot position relative to load and coefficient of friction at foot-floor interface play such an important role that there were severe limitations on the practicality of recommendations in a working situation where these factors were out of the worker's sphere of influence. Furthermore if one considers the differing relationships between load and hand force exertion detailed in Table XVIII and Figure 17, it appears that it would be important to recommend hand force exertion limits rather than weight limits.

Interaction of load & technique: initial and sustained phases

When considering the effects of load and technique it is important to determine not only the singular effects of these variables, but additionally if any interaction effect occurs between them. Interaction effects were only statistically significant in the initial and sustained phases (shown in Figure 17). With respect to the ending forces statistically there was no interaction effect between load and technique.

The impact of technique on hand forces is dependent on the load being moved (Figure 17). Differences between techniques at 250kg are statistically negligible whilst at 500kg the differences become more apparent. At this heavier load pushing elicited significantly higher hand forces than one or two handed pulling, for both initial and sustained phases. These findings suggest that at low loads there is no preferential technique; however as load increased so pushing elicited increasingly high hand forces.



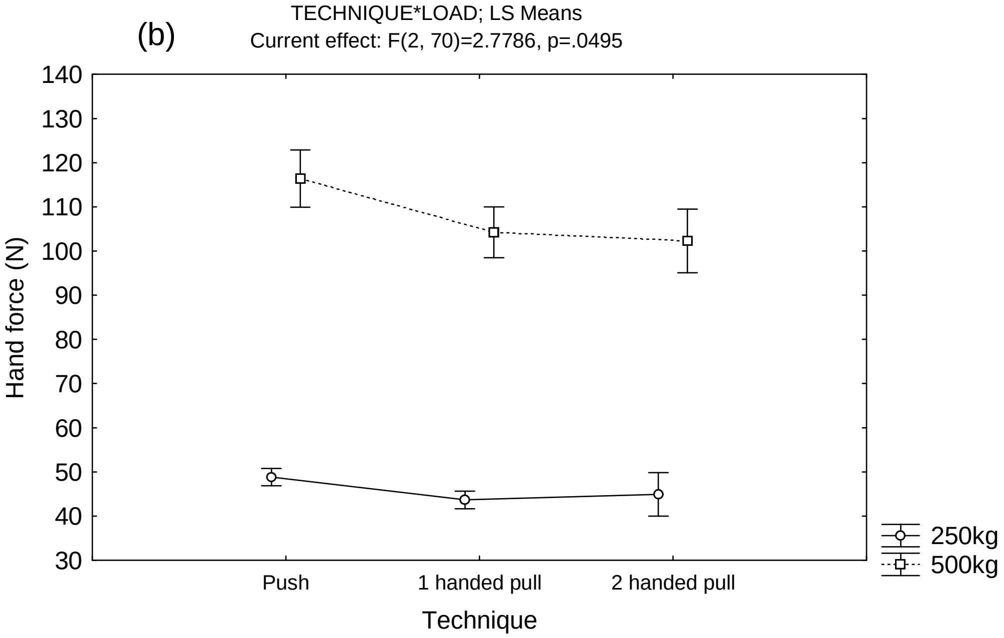


Figure 17: Interaction effects between load and technique for (a) peak initial and (b) average sustained forces.

Nevertheless, despite these findings, it is important to consider responses holistically. Although hand forces are greatest during pushing, current results indicate that muscle activity and body discomfort indicate the opposite whereby pushing is the preferable technique. This serves to demonstrate the importance of considering a range of human responses to push/pull tasks rather than concentrating solely on one.

Related studies have not considered interaction effects of factors that influence pushing and pulling and thus these results cannot, as yet, be corroborated. The current results do however indicate that interaction effects appear important and therefore require further investigation. These interaction effects, if quantified, may play a role in explaining the relationship between factors outlined by Mack **et al.** (1995) and Jung **et al.** (2005) and aid in elucidating the multifaceted association between design, task, environment and operator factors that influence operator responses to pushing/pulling tasks.

Ending phase

Literature relating to ending phase hand forces is sparse compared to the other two phases of pushing and pulling. One comparable investigation utilised a light load of 58.8kg yet found ending force values ranging between 62N and 112N (Jansen **et al.**, 2002), similar to those evidenced in the current investigation. Several important methodological differences exist between the two studies and this example aids in emphasising the suggested importance of factors other than load mass that influence hand forces when stopping a wheeled trolley. Jansen **et al.** (2002) instructed workers to push at 'work pace' and thus was self paced as compared to the current strictly controlled walking velocity. Floor types in Jansen **et al.**'s (2002) study were linoleum and carpet (hard and soft surfaces) but the coefficient of friction is not detailed; these floor types are arguably dissimilar to the plywood used in the present walkway.

For the current study to elicit similar ending forces (96N-100N) whilst at a significantly higher load (250kg) would indicate the likelihood that factors other than the load play a role in determining ending forces. These extraneous variables include floor type/friction, walking velocity and acceleration/deceleration technique. These findings imply the importance of velocity in the ending phase; higher trolley velocity is likely to be related to higher hand force responses, even at low loads. Faster movement speed has been linked to greater physical stress

(Jung **et al.**, 2005). In the existing investigation it was observed that, despite comprehensive instructions, some participants stopped the trolley more abruptly than others. These individuals typically recorded the highest peak ending forces. This would suggest that using a gradual technique to halt the trolley would be beneficial in terms of reducing peak ending forces and therefore the forces experienced by the musculoskeletal system. Results thus advocate the education of workers in the use of appropriate stopping techniques.

However, it is important to acknowledge that the standard deviations evidenced in the ending phase are relatively low, thus suggesting that variations in stopping time, while important, are not necessarily the driving factor. Rather the environmental factors such as load, wheel/floor friction and trolley maintenance remain the most important factors in reducing the physical demands of the task. Nevertheless education of workers may help to reduce hand forces somewhat, particularly in situations where the environmental issues have been addressed and improved as far as possible.

ELECTROMYOGRAPHY

Electromyography (EMG) within gait research has been used to identify normal and pathological gaits as well as for rehabilitative purposes (Kleissen **et al.**, 1998; Ricamato and Hidler, 2005). Although EMG has been extensively used in recent Ergonomic investigations, allowing relatively easy access to previously unobservable physiological processes, there has been little focus on EMG during pushing and pulling, particularly in the lower extremities. EMG plays a role in investigation of muscular fatigue and has been recommended as a supplementary evaluation alongside other biomechanical measures to investigate gait responses (Basmajian, 1974; Redfern, 1992). Furthermore muscle activity plays a key role in clarifying the demands placed on the musculoskeletal system and may help to identify both fatigue risk and chance of overexertion.

Normal forward and backward walking

In order to determine the additional demand being placed on the body by the pushing/pulling conditions, control conditions of normal, unloaded forward and backward walking were included in the experimental design. These provided a 'baseline' from which to assess the additional muscle activity demanded by the inclusion of a load movement task. When considering the normal walking conditions, it was found that in three of the four muscles observed, activity was significantly higher in the backward walking conditions. This indicates that, independent of any load movement, backward walking may place workers under greater physical demand than does forward walking; thus arguably workers would fatigue quicker in backward walking tasks such as two handed pulling. Grasso **et al.** (1998) further suggest that the rate of EMG increment with speed is generally higher in backward walking, thus if walking speed is increased, muscle activity in backward walking is affected to a greater extent than during forward walking.

When comparing the present results to normative values there are several methodological issues that hamper the comparisons; unfortunately there are few studies considering forward/backward walking that detail %MVC results for similar muscles, thus comparisons to the literature are limited. Of the studies that do exist Ericson **et al.** (1986) report EMG activities (for normal forward walking) of 10% MVC for BF, 19% for gastrocnemius (lateral head) and 27% for TA. These are similar to the 12% MVC (BF) and 17% (MG) observed in forward walking in the current study (Table IX, page 67).

It is argued that velocity plays a major role in determining muscle activity during gait (Winter, 1991; Stoquart **et al.**. 2008) such that higher walking velocity leads to greater levels of muscular activation. This is supported by the significantly higher %MVC results recorded between forward and backward walking detailed by Grasso **et al.** (1998) when using a walking speed of 1.01 $m.s^{-1}$ (significantly faster than the present 0.45-0.55 $m.s^{-1}$). It is interesting that the EMG results detailed by Ericson **et al.** (1986) are similar to current results as those authors detailed a faster cadence (and therefore walking speed). This is an anomaly amongst the related gait literature and serves as a reminder of the complex interactional relationship between variables in dynamic EMG investigations.

Grasso **et al.** (1998) further compare results from other investigations (Dubo **et al.**, 1976; Lyons **et al.**, 1983) where higher levels of muscle activity were observed for the relevant muscles. This variation is explained by differences in age, sex, physical fitness and EMG normalisation methods (Dubo **et al.**, 1976; Lyons **et al.**, 1983). Two decades on this helps to elucidate discrepancies between muscle activation results from the current study and those in the literature. Thus it is difficult to validly compare muscle activation results, even when normalised; it is therefore advised that results should only be extrapolated to populations with similar characteristics to the current sample group. These issues further indicate the limitations inherent within EMG research and must be acknowledged when analysing EMG responses.

Control vs. experimental conditions

When comparing the control and experimental conditions, pushing and one handed pulling were compared to forward walking and two handed pulling was compared to backward walking. Table XXI details the additional muscular cost induced by pushing/pulling; these were calculated by subtracting the normal walking 'baseline' muscle activity data from that obtained during push/pull conditions.

Table XXI: Additional muscular cost incurred by pushing/pulling.

		RF (%MVC)	BF (%MVC)	MG (%MVC)	TA (%MVC)
Push	250kg	**1.7**	2.1	**11.3**	7.0
	500kg	**7.0**	**2.8**	**16.3**	**14.0**
1 H pull	250kg	**5.1**	**4.4**	**13.4**	**8.5**
	500kg	**11.1**	**7.1**	**13.4**	**8.5**
2 H pull	250kg	**1.9**	3.9	3.0	5.5
	500kg	**5.9**	**3.0**	**9.1**	**7.6**

Where **red** figures indicate statistically significant differences between control and push/pull condition

Additional muscular cost caused by pushing/pulling ranges from 1.7% MVC to 16.3% MVC (RF and MG respectively). In all cases the additional burden of moving a wheeled load resulted in an increase in muscle activity, necessary to provide the requisite force to allow individuals to effectively move the load. In the majority of cases this increase in muscle activity was statistically significant. Increases in muscular demand are lower at both loads for pushing as opposed to one handed pulling. Increases in activity during two handed pulling (at both loads) are relatively lower than one handed pulling, but similar to those elicited during pushing.

Technique effects on additional muscular demand are illustrated in Figure 18. At both loads two handed pulling evokes the lowest extra muscular cost 75% of the time. At 250kg pushing elicits lower supplementary cost than one handed pulling, whilst at 500kg this trend occurs 50% of the time. From a muscular activation perspective, therefore, it would appear that two handed pulling is the technique likely to place the lowest additional cost on the worker, but this is only true when compared to backward walking.

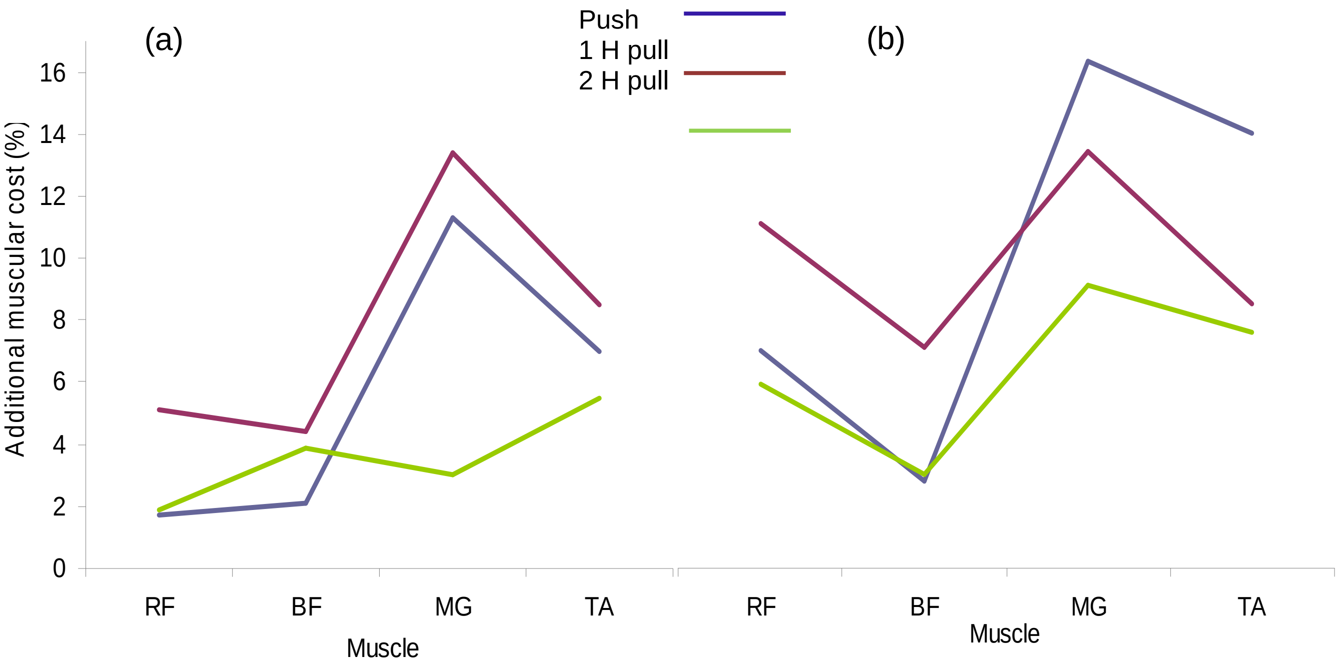


Figure 18: Effect of technique on additional muscular cost in (a) 250kg and (b) 500kg loads.

In consideration of these results, the intrinsic burden of backward walking must be acknowledged. To achieve this, additional muscular costs of two handed pulling on responses were calculated as compared to forward walking and then compared to the remaining techniques (thus creating an alternative baseline comparison). An example of this can be seen in Figure 19 where the additional muscle activation responses to load movement are displayed for all load/technique combinations for the Rectus femoris muscle (to be succinct a single muscle was chosen to illustrate this argument). In this case, the load/technique combinations were compared to forward pushing to eliminate the masking effect of backward walking responses. It is important to recognize that although load appears to affect two handed pulling least when it is compared to backward walking, this is not necessarily the case when taken as a comparison to forward walking.

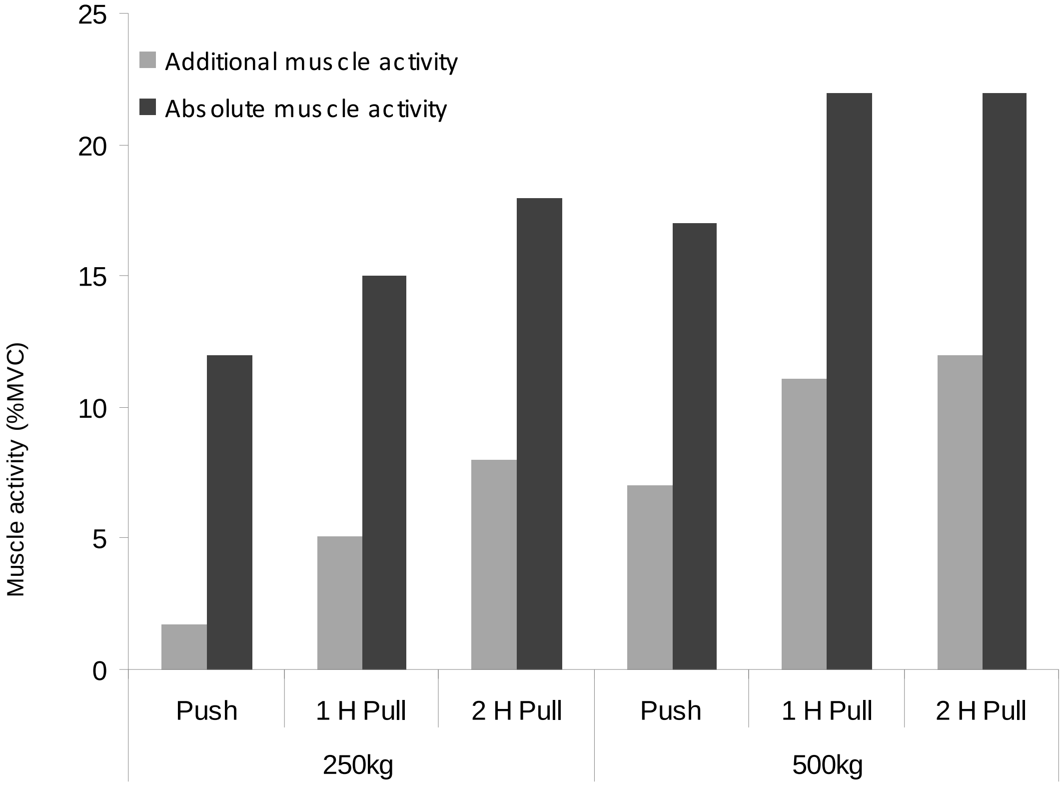


Figure 19: Additional muscular cost (in Rectus femoris) when compared to unloaded forward walking.

It was found that additional muscular cost of two handed pulling as compared to forward walking was higher than that elicited during pushing and one handed pulling when regarding lower limb muscle responses. This is illustrated in Figure 19 where additional muscular cost is greatest in two handed pulling when compared to unloaded forward walking at both loads. These findings further suggest that pushing would place the least additional muscular demand on the worker (from both an additional and absolute muscle activity perspective) and therefore would be most preferable. According to lower limb muscle activity absolute responses in the Rectus femoris, at lower loads two handed pulling would be least preferable whilst at higher loads the distinction between pushing and one handed pulling remain ambiguous.

Acknowledgement must be made of the asymmetrical nature of one handed pulling tasks; research has shown that symmetrical tasks are preferred for reducing injury risk (Marras **et al.**, 1995; Marras and Mirka, 1990); based on the results detailed here, this should arguably be extended to include pushing/pulling tasks. Although not expressly considered in this study, it would be important to consider the likelihood of additional risk being placed on the musculoskeletal system by asymmetrical one handed pulling, particularly in the upper body. The results concur with the findings of Li **et al.** (2008) whereby two handed pulling was preferred over one handed pulling at higher loads. This symmetrical technique allows for the full use of body weight to provide momentum to move wheeled loads and thus would arguably require less muscular effort from the arm and shoulder regions, lowering the undesirable asymmetrical nature of one handed pulling tasks.

GAIT PATTERN RESPONSES

While gait patterns have been extensively researched, controversy concerning even the most basic aspects of locomotion remains (Zatsiorsky **et al.,** 1994) and gait in the workplace has been scarcely researched (particularly in the case of pushing and pulling), despite being an integral part of dynamic load movement tasks.

Stride length and cadence

When compared to previous gait research the results for stride length are comparable, with Perry (1992) suggesting that ‘normal’ male stride length is 1.46m. A similar mean stride length of 1.4m was observed in the current sample, for forward unloaded walking. There is little research on backward walking 'norms', however it was seen that individuals took more, smaller steps during backwards walking, as reflected by the slightly higher number of strides (NF 5 strides, NB 6 strides) and shorter stride lengths(NF 1.4m, NB 1.1m). Industry is likely to require workers to push/pull either more frequently or over longer distances than observed in the present study; either requisite is liable to have an impact on gait responses. If required to push/pull frequently throughout an 8 hour shift, an extra stride on each push/pull during backward pulling may significantly impact both muscular demand and risk of ST&F incidents. Similarly in the case of further push/pull distances small differences in stride parameters may become important. To illustrate this, Table XXII extrapolates the stride differences from the observed 7 m to a hypothetical 100m movement distance.

Table XXII: Effect of distance on stride differences.

Condition	Number of strides	Number of strides over 100m
NF	5	71
NB	6	86
Push (250kg)	5	71
Push (500kg)	5	71
1 Pull (250kg)	5	71
1 Pull (500kg)	6	86
2 Pull (250kg)	6	86
2 Pull (500kg)	7	100

While it can be seen that there is little difference between numbers of strides taken for the various conditions (over the 7 m testing distance), the difference becomes more apparent over longer distances. A difference of 29 strides per 100m between lowest and highest values exists in the hypothetical situation, with the greatest number of strides taken during two handed pulling at 500kg (Table XXII). As this shows, shortening of stride length and increased cadence is likely to become significant with increased movement distance. Furthermore this may play a role in increasing energy expenditure due to higher muscle activation levels. Investigation of energy expenditure was outside the scope of the current study, but is strongly suggested as an area of future research, required to more fully elucidate the demands of pushing/pulling, particularly physiological demands.

The slow walking speed in the current study strongly influences the cadence obtained (78 steps.min^{-1}) such that it is much lower than conventional ‘norms’ (111 steps.min^{-1} according to Perry (1992)). This makes comparison to normal values difficult however some comparison can be made between the current results and those detailed by Stoquart **et al.** (2008) whose protocol involved walking at similar speeds (1, 2 and 3km.h^{-1} or 0.27, 0.55 and 0.83 m.s^{-1} as compared to 0.76 - 1.0m.s^{-1} in the present investigation). Stoquart **et al.** (2008) report speed dependant relationships in both gait and EMG responses, with cadence values of 52 ±12 steps.min^{-1}, 76 ±7 steps.min^{-1} and 93± 7 steps.min^{-1} for the speeds detailed. Similarly Murray **et al.** (1985) report cadence values of 87 ±2.5 steps.min^{-1} for individuals walking at a ‘slow pace’ over ground. These values are similar to those reported in the current study, suggesting that these results are comparable to studies performed at similar speeds. Using comparison to normal unloaded walking, the absolute results indicate that gait during pushing/pulling is not vastly different to unloaded walking when considering the number of strides taken. At longer distances or greater frequencies this may however alter; in the case of one handed pulling at 500kg, the additional stride taken over 7m relates to an increased 15 strides over 100m. Accordingly cognisance must be paid to the effect of increased movement frequencies and distances when applying these results to an industrial context.

Stride duration and foot contact times

The Tekscan FlexiForce A201 Variable Resistance Sensors allowed for more complex measures of gait pattern responses. Measures were calculated in relation to the gait cycle shown in Figure 3 (page 25) to allow for comparison to past gait literature. These sensors acted in a similar fashion to footswitches and allowed collection of temporal data, integral for investigation of gait; measures such as stride duration and contact times (stance, swing, double support and single support) are the cornerstones of gait research (Patla, 1985; Perry, 1992). Unfortunately there is scant literature regarding gait analysis of pushing/pulling, therefore any comparisons to literature are limited to conventional gait analysis studies.

What is immediately obvious from the results of gait analysis for the current study is that many of the contact time values (measured as a percentage of the gait cycle) are higher than expected ‘normal’ values. For example, gait literature suggests that the stance phase normally corresponds to approximately 60% of the gait cycle (Wall **et al.**, 1987; Whittle, 1991; Perry, 1992; Zatsiorsky **et al.**, 1994) whereas current results indicate 72-76% stance values. Nonetheless this can be explained in terms of walking speed variations. Standard stance phase values have historically been based on individuals walking at a ‘normal’ pace, or approximately 4km.h^{-1} (1.1 m.s^{-1}). The current walking velocity was set at 0.45-0.55 statures.s^{-1} which, given the stature ranges of the participants, equates to 0.76-1.0m.s^{-1}, thus individuals were walking significantly slower than ‘normal’ walking pace. For this reason, higher foot contact times are expected. This is supported by the findings of Stoquart **et al.** (2008) where low velocity walking resulted in higher stance phase measurements than ‘normal’ values. At speeds of between 0.27m.s^{-1} and 0.83 m.s^{-1} these authors reported stance contact of 66-77% with higher values being recorded at the slower walking speeds.

Stride duration was measured as part of the investigation into the temporal gait responses during various loading conditions. Current stride duration was observed within the range of 1.38s-1.47s, with particularly low intra-individual variation. Differences between backward and forward walking were not statistically significant, although slightly lower stride duration was observed in backward walking. When pushing (250kg and 500kg) individuals took longer (1.47s as opposed to 1.43s for normal forward walking) to complete strides. This was possibly as a result of the additional support afforded by the trolley handle as well as the forward leaning posture that this support allowed (see Figure 15, page 78).

When compared to the literature, Auvinet **et al.** (2002) report normal male (20-29 years) stride durations of 1.65s (walking velocity of 1.59m.s^{-1}) while previous observations set by Murray **et al.** (1964) suggest 1.04s at a cadence of 115 steps.min^{-1}. These stride durations are comparable to those found in this study, given the differences in walking velocity (and thus cadence) evidenced between the various studies. What is interesting to note when considering the remaining gait responses is the lack of significant differences between the experimental push/pull conditions and normal unloaded walking. Foot contact times, double and single support all displayed parameters significantly similar to normal, unloaded walking.

In addition to the lack of conclusive evidence returned by the current gait pattern results, at present insufficient studies have been conducted in this area to make valid conclusions regarding the effect of pushing/pulling on gait pattern responses. Nevertheless the importance of the current findings lies in the fact that it appears that pushing and pulling do not impact the gait parameters measured. Thus differences in these variables cannot be used to explain the increased likelihood of slip, trip and fall incidents that has been evidenced during pushing and pulling (Grieve, 1983; Lipscomb **et al.**, 2006; Li **et al.**, 2008). It is likely that factors such as frictional forces at the foot-floor interface remain vitally important in determining slip risk; increased interest in this parameter is important for determining the mechanisms behind slip, trip and fall accidents during pushing/pulling (Haslam **et al.**, 2002; Boocock **et al.**, 2006; Li **et al.**, 2008).

PSYCHOPHYSICAL RESPONSES

Body discomfort

Evans and Patterson (2000) advocate the use of subjective responses of discomfort as indicators of potential musculoskeletal problems as well as insights into individual perceptions of a work task. In the current study individuals were not forced to rate discomfort if they felt it to be unnecessary. While some individuals chose not to rate discomfort, the number and intensity of ratings that did occur is concerning. 53% of participants rated the calves as experiencing discomfort (intensity 3/10) during two handed pulling, while 19% indicated discomfort in the upper extremity (intensity 3/10) during unilateral pulling of the heavier load.

Considering the long rest breaks (60s between repetitions) and infrequent nature of the task (3 repetitions per condition), body discomfort ratings as seen in the present results indicate a serious concern for musculoskeletal disorders. In workers that would perform these tasks frequently over an 8 hour work shift these discomfort ratings indicate a host of potential upper and lower body musculoskeletal problems. Unfortunately the lack of perceptual focus in push/pull studies hinders comparison to these results. In a related study conducted at Rhodes University Cripwell (2007) noted that the calves were cited most frequently as experiencing discomfort, particularly at higher frequencies of push/pull. Furthermore Cripwell (2007) identified the shoulder as an area of concern; Hoozemans **et al.** (2004) mention the increasing prevalence of shoulder injuries related to pushing and pulling. This supports the current findings, particularly in one handed pulling where shoulder complaints are likely to arise.

Considering the impact of load on perceptual responses, individuals rated more discomfort of higher intensity during movement of the heavy load as opposed to the lighter load, a finding that concurs with the general trends found relating to load being a major cause of greater biomechanical demands on the body. Thus increases in load are clearly perceived as creating higher physical demands, as well as being supported by biomechanical responses. This has severe implications within industry where a range of different, and significantly higher, loads are likely to occur.

To summarise these findings, one handed pulling was perceived as creating the most discomfort in the upper body, particularly at the heavier load. Conversely the calves were the most consistently rated body region with the greatest concern occurring during two handed pulling at 500kg. The infrequent nature of push/pull tasks in this study were sufficient to create discomfort both in the upper and lower body and thus are of concern in industry from a psychophysical acceptability standpoint.

INTEGRATED DISCUSSION

Individual contributions of biomechanical and perceptual approaches to a task allow for elucidation of mechanisms underlying the demands of a dynamic push/pull task. However it is through integration of these approaches that the full complexity of these demands is more fully appreciated. Furthermore if recommendations are to be made to industry, it is important to use the knowledge gained in each domain to create appropriate, holistic guidelines.

Table XXIII illustrates the dependent variables that were significantly different in each case when experimental conditions are compared. Load plays a significant role in determining magnitude of responses with higher loads having the greatest impact on biomechanical and perceptual responses. This is shown by the higher percentage of significant differences occurring at 500kg as opposed to 250kg. Conversely, technique only significantly affected select variables and there is a lack of consistency between dependent responses that hinders the outright recommendation of any particular technique.

Table XXIII: Significant differences in biomechanical and perceptual responses occurring between the experimental conditions.

Condition	Push (250)	Push (500)	1 H pull (250)	1 H pull (500)	2 H pull (250)	2 H pull (500)
Push (250)		PI, S, PE, TA		PI, S, PE, RF, TA	RF, TA	PI, S, RF, TA, GP
Push (500)	44		PI, S	PI, S	PI, S, MG	
1 H pull (250)	0	22		PI, S, PE	RF	PI, S, EP, RF
1 H pull (500)	55	22	33		MG	
2 H pull (250)	22	33	11	11		PI, S, PE, MG
2 H pull (500)	55	0	44	0	44	

Variables in the upper half of the matrix indicate variables which ***are*** significantly different between conditions. Figures in the lower half represent the percentage (%) of variable responses that are different.

Where: PI= peak initial force, S= sustained force, PE = peak ending force, RF = Rectus femoris, BF = Biceps femoris, MG = Medial gastrocnemius, TA = Tibialis anterior, GP = gait pattern, BD = body discomfort

Assimilation of this information may provide some conclusions and recommendations; Table XXIV summarises the current findings with the aim of providing recommendations. Table XXIV further demonstrates the disparity found between different dependent variable responses; this supports Dempsey's (1998) proposal that as different approaches (biomechanical, physiological and perceptual) often produce conflicting results, it is important that as many variables as possible are taken into account, providing Ergonomists with an holistic perspective of pushing/pulling tasks.

Table XXIV: Summary of results showing effect of technique on dependent variables, ranked best and worst techniques.

		250kg		500kg	
		Best technique	Worst technique	Best technique	Worst technique
Hand forces	Peak initial	1 H pull	Push	1 H pull	Push
	Sustained	2 H pull	Push	1 H pull	Push
	Peak ending	2 H pull	1 H pull	2 H pull	1 H pull
	Muscle activity	Push	2 H pull	Push	1 H pull
	Gait patterns	Push	2 H pull	Push	2 H pull
Body discomfort	Upper body	Push	1 H pull	Push	1 H pull
	Lower body	Push	2 H pull	Push	2 H pull

In terms of hand force exertion, pushing elicited the highest hand forces during the initial and sustained phases; the ending phase reflected greatest forces induced during one handed pulling. However, in the remaining dependant variables, pushing was shown to be the preferable technique, eliciting lowest muscle activity and perceived strain. Responses were seen to be highly dependent on load in the present case; at lower loads two handed pulling was, on average, the least preferable technique whist at higher loads one handed pulling was least appropriate.

The disparity between preferred technique according to hand force exertion and muscle activity indicates a poor correlation between the two. Furthermore the fact that pushing elicited the highest hand forces but the lowest muscle activity and discomfort ratings suggests that hand forces may not necessarily be the best indicator of physical strain being experienced by the worker. This would support Hoozemans **et al.**'s (2004) argument that hand forces are a poor indicator of the mechanical load placed on the musculoskeletal system, particularly in the shoulder and lower back regions. Other factors such as movement, posture and direction of joint loading may be more important and therefore future research is required for clarification.

CONCLUSION

Regardless of the load moved, pushing is the most preferable technique; it evidenced the majority of the best biomechanical and perceptual responses. If this technique is not feasible, the choice of pulling technique is dependent on load. While unilateral pulling may be tolerable at low loads, higher loads are likely to require a two handed pulling approach to avoid increased risk of musculoskeletal disorders. However, the impact of technique cannot be taken in isolation and other important factors, such as wheel/floor friction, have been shown to have an impact on the chosen technique. Furthermore the apparent contradictions between the current responses to pushing/pulling highlight the significance of Dempsey's (1998) statement regarding the importance of a holistic integrated approach; Ergonomic research in the current field needs to acknowledge this fact and conduct research accordingly. Consequently, future research acknowledging not only biomechanical and psychophysical responses but also physiological responses is vital.

CHAPTER VI

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

INTRODUCTION

Manual materials handling (MMH) tasks remain prevalent within industry: consequently associated musculoskeletal disorders persist as a major concern for Ergonomists. Increased awareness regarding the relationship between lower back pain and lifting has led to the recognition that lifting is biomechanically and physiologically detrimental to workers (Resnick and Chaffin, 1995). Subsequent attempts to reduce lifting components within MMH tasks have led to a concomitant rise in pushing and pulling using manual handling devices (MHD) such as wheeled trolleys and hoists (Hoozemans **et al.**, 1998). Ergonomic research into pushing and pulling has yet to provide a comprehensive understanding of the associated physical demands despite the epidemiological links that have been drawn between pushing/pulling and musculoskeletal disorders (Lee **et al.**, 1991; van der Beek **et al.**, 1999; Hoozemans **et al.**, 2004).

Several authors concur that pushing (as compared to either form of pulling) imposes the least strain on an individual from a biomechanical perspective (David and Nicholson, 1985; Schibye **et al.**, 2001; de Looze **et al.**, 2000); unfortunately MHD specificity and workplace related factors commonly reduce the viability of this technique. As a result, one and two handed pulling are often employed. Differences between these techniques have yet to be fully elucidated, thus advice to industry in terms of recommended push/pull technique is limited in scope.

Hand force exertion has commonly been used to indicate mechanical loading on the musculoskeletal system and is divided into initial, sustained and ending phases (van der Beek **et al.**, 1999). Pushing/pulling contain both static (upper body) and dynamic (lower body) muscle activity, yet little attention has been paid to the integral dynamic component of walking. This element is a contributing factor to muscular fatigue and is likely to be related to musculoskeletal injury and reduced endurance time. As a result, muscle activity responses to push/pull tasks are virtually unknown, particularly in relation to backward and forward walking components, limiting the ability of Ergonomists to identify potential injury risk. Furthermore Todd (2005) identified gait pattern responses as an area of deficit within push/pull research; this is of concern in view of the acknowledged link between gait and slip, trip and fall accidents particularly on reduced friction floors (Winter, 1995; Boocock **et al**., 2006; England and Granata, 2007).

This study undertook an integrated biomechanical and psychophysical approach to investigating six combinations of technique and load (used to manipulate task demands) during dynamic pushing and pulling tasks. This was to determine the impact that these differing task demands have on workers. Taking into account several under researched responses, the current study aimed to contribute to the existing body of knowledge surrounding the physical and perceptual demands of push/pull tasks.

SUMMARY OF PROCEDURES

The present study was conducted in a laboratory environment in the Department of Human Kinetics and Ergonomics at Rhodes University. Six experimental conditions provided the basis of the study, with participants being required to move two loads of 250kg and 500kg using three techniques (forward pushing, forward unilateral pulling and backward two handed pulling). Furthermore to allow for comparison of muscle activity and gait pattern responses, two control conditions of normal unloaded forward and backward walking were performed. Experimentation was performed on a 10m, friction-controlled plywood walkway at a controlled relative speed of 0.45-0.55 statures.sec^{-1} using a pallet jack trolley. The independent and dependent variables, restrictions and delimitations were set subsequent to extensive pilot testing.

A sample group of healthy Rhodes University male students volunteered to participate in this study. The sample comprised the following mean anthropometric characteristics: age 21 ±2 years, stature 1791 ±43 mm and body mass 77 ±10 kg. Each participant performed six experimental conditions and an additional two unloaded control conditions. Individuals were required to attend an extensive habituation session and a ninety minute experimental session; the experimental and control conditions were performed during the latter. Each condition was completed after the performance of three successful trials, with adequate work-rest ratios protecting against cumulative fatigue.

The biomechanical responses measured included hand force exertion in the initial, sustained and ending phases; obtained using a Chatillon^{TM} load cell attached to the pallet jack handle. Muscle activity was recorded in the Rectus femoris, Biceps femoris, medial gastrocnemius and Tibialis anterior muscles, representing the four major muscle groups of the lower extremity. These were normalised by making results relative to individual maximal voluntary contractions (MVC), hence allowing valid inter-subject comparison. Additionally gait pattern responses were taken directly, using observation, (stride length and cadence) and indirectly using Tekscan FlexiForce A201 Variable Resistance Sensors (foot contact patterns and timing) placed in standardised positions within industrial work boots. Finally perceptual responses were observed through use of the modified body discomfort (BD) scale adapted from Corlett and Bishop (1976).

Basic descriptive statistics were run on the observed variables, providing general information regarding the sample as well as checking assumptions of normality. Two way ANOVAs allowed comparison between the load/technique combinations for hand force, muscle activity and gait pattern responses. One way ANOVAs were performed with respect to hand forces during the motion phases to determine differences between the initial, sustained and ending phases. Student T-Tests were performed to determine differences between unloaded forward and backward walking for muscle activity and gait pattern responses. Repeated measures ANOVAs were used to analyse muscle activity and gait pattern differences between control and experimental conditions.

SUMMARY OF RESULTS

Biomechanical responses

With respect to hand force exertion, it was found that initial, sustained and ending forces were all significantly ($p<0.05$) affected by load. When load was increased from 250kg to 500kg, hand force exertion response increased (averaged across techniques) 35%, 77% and 30% for initial, sustained and ending phases respectively. The highest forces occurred during pushing at 500kg in the initial and sustained phases (333 ±29 N and 116 ±8 N respectively). On the contrary, during the ending phase two handed pulling at 500kg evoked the highest hand forces (155 ±28 N). When considering the effect of technique, initial and sustained phases at the heavier load evidenced pushing creating significantly higher hand forces than either one or two handed pulling whilst the differences in pulling conditions were not significant. Technique had no significant impact on ending forces at either load.

The majority of the hand forces observed in this study were within acceptable limits according to established conservative guidelines, with the exception of the peak initial forces at 500kg for all three techniques. This indicates that these three conditions would place undue strain on the subjects' musculoskeletal systems and thus could lead to fatigue and/or injury. Initial forces were found to be significantly higher than sustained and ending forces whilst ending forces were significantly higher than sustained forces ($p<0.05$), indicating that the greatest strain is experienced during the initiation of movement. The linear relationship between load and hand forces allows for extrapolation; however the interplay of task and environmental factors means that this relationship is unique to each workplace situation and due care is required when extrapolating data in industrial situations.

Muscle activity responses showed that backward walking required significantly higher muscle activation than did forward walking (37%, 14% and 27% for Rectus femoris, Biceps femoris and Tibialis anterior respectively). Gastrocnemius elicited similar responses in both movement directions where no significant differences occurred. This suggests that backward walking inherently places higher muscular demand on individuals. With respect to muscle activity responses to pushing/pulling, it was found that moving a load significantly increased muscle activity over and above that observed during unloaded walking. Additional muscular demand ranged between 1.7% and 14% MVC, with 79% of the responses being significantly higher when compared to unloaded walking. At lower loads pushing elicited the lowest muscle activity in all of the observed muscles whilst at higher loads this was the case 50% of the time; these technique differences were not however statistically significant. The relationship found between forward and backward walking may not necessarily hold true during pushing/pulling tasks. The impact of load movement therefore outweighs the differences between forward and backward walking so although there may be differences, these are masked by the much larger impact of load.

At 250kg, two handed pulling evidenced the highest muscular activation of the three techniques. However an additional load (up to 500kg) did not result in a concomitant increase in muscle activity during this technique, suggesting that the relationship is not linear. At lower loads, two handed pulling was the most taxing, however as load increased, so one handed pulling resulted in greater muscular demands than two handed pulling. Moreover when the two handed pulling conditions were compared to forward walking (thus eliminating the bias of intrinsically higher backward walking muscle activity), pushing remained the least demanding technique, even at higher loads. The high levels of inter-individual variation evidenced are common within muscle activity investigations, nevertheless responses during the control conditions were comparable to previous literature regarding normal walking.

Gait pattern responses in the present study evidenced comparable control results to related studies performed at similar speeds. Importantly, very low intra individual variation between trials was observed with respect to gait responses. Mean stride length during unloaded forward and backward walking were 1.4m and 1.1m respectively and no significantly different responses were found between experimental conditions. Stride duration was consistent across control and experimental conditions within the range of 1.37-1.47s and did not vary significantly between forward and backward walking ($p>0.05$).

Responses for foot contact times were higher than the expected norms; foot contact times ranged between 70 and 76% as opposed to ‘normal’ 60% of the gait cycle. This was however due to the slow walking speed utilised in the current study. Right and left foot contact times and single support responses were similar during unloaded walking and push/pull conditions. The remainder of the gait pattern responses were not statistically affected by pushing/pulling, thus neither load nor technique significantly affected foot contact times, single or double support.

These results indicate that pushing and pulling did not significantly alter observed gait pattern responses in comparison to normal walking. It appears that incidences of slip, trip and fall incidents are therefore not related to the investigated gait parameters. However the current pushing/pulling tasks were performed at relatively slow walking velocities, thus it is uncertain whether pushing/pulling would have an impact on slip, trip and fall risk at higher walking speeds; this is of importance and should be addressed in future investigations. Additionally, cognisance must be taken of the importance of the shear forces occurring at the foot/floor interface that have been identified as contributing factors to slipping whilst pushing/pulling (Haslam **et al.**, 2002). The current results have illustrated that at slower speeds, gait responses are unlikely to be responsible for slip, trip and fall accidents. A small number of studies have considered the implication of frictional forces on slip risk (Fox, 1967; Grieve, 1983; Haslam **et al.**, 2002; Boocock **et al.**, 2006; Li **et al.**, 2008) and the current results support the ongoing investigation of factors such as these to aid in clarification of mechanisms behind slip, trip and fall incidents.

Psychophysical responses

When considering perceptual responses, body discomfort gave an indication of potential risk areas of musculoskeletal injury as well as subjective perceptions of pushing/pulling task demands. The highest ratings of discomfort were experienced in the calves during two handed pulling; the calves were rated as experiencing discomfort in all six experimental conditions (42 ratings, average intensity of 3/10). The biceps and shoulders were also identified as areas of potential concern, particularly in one handed pulling where discomfort was concentrated solely in the arm used to pull the loaded pallet jack. Increased discomfort ratings were seen at higher loads and indicates that load played a role in determining the subjective perception of task demands. Results regarding the effect of technique on body discomfort suggest that the upper body experienced the most discomfort during one handed pulling while two handed pulling evoked the most discomfort in the lower extremities. In general pushing elicited the least discomfort in both the upper and lower body, suggesting that this technique is perceptually the most preferable.

STATISTICAL HYPOTHESES

Biomechanical hypotheses

Effect of load

Hypothesis 1 (a) (i):

This hypothesis stated that no differences existed between the biomechanical responses at the 250kg and 500kg loads.

With regard to hand forces this hypothesis is rejected as responses at the two loads were significantly different to each other across all techniques and all motion phases. Load therefore played a significant role in determining hand force magnitude.

With reference to muscle activity, load had a significant impact on three of the four muscles. However, post hoc analysis revealed that significant differences were only observed in three out of twelve possible combinations, with each technique evidencing load effects in a single case. This leads to the tentative retention of this hypothesis.

Gait pattern responses were not significantly affected by load, therefore the hypothesis is tentatively retained.

Effect of technique

Hypothesis 1 (a) (ii):

The hypothesis under test stated that there would be no differences between pushing, one handed pulling and two handed pulling for hand force, muscle activity and gait pattern responses.

With respect to hand forces, two of the three motion phases (initial and sustained) evidenced significant technique effects, however post hoc analysis revealed that only three of eighteen combinations were statistically different. This led to the tentative retention of this hypothesis. Despite the retention of the null, in all of the cases where significant differences were evident, pushing was found to elicit significantly higher hand forces than pulling.

Significant technique effects were observed in three of the four muscles with two of eighteen combinations demonstrating a significantly different response during post hoc analysis. Although the null is tentatively retained, it is important to note that in both cases of significance, pushing was shown to elicit the lowest muscular demand.

Technique had a significant impact on two gait pattern responses; however this significance was not apparent during post hoc analysis, suggesting that when considered individually, technique has no effect on gait pattern responses. The null hypothesis is therefore tentatively retained.

Hypothesis 1 (b)

The hypothesis tested proposed that there would be no difference between the initial, sustained and ending forces for different load/technique combinations. This hypothesis is rejected as significant differences were found between hand forces for all three movement phases.

Hypothesis 2 (a) (i)

The hypothesis under test suggested that there would be no difference in either muscle activity or gait patterns as a result of load movement (during pushing and one handed pulling) as opposed to unloaded forward walking.

With respect to muscle activity this hypothesis is rejected as responses revealed significant differences between both pushing and one handed pulling responses and unloaded forward walking. This was the case in fourteen of the sixteen combinations.

Considering gait responses, only one dependent variable (duration) had a significant effect on gait responses when comparing pushing and one handed pulling to the control condition of unloaded forward walking. Therefore in this case the null hypothesis is tentatively retained. Post hoc analysis revealed that while the significant effect was present overall, no individual cases of significant difference were found.

Hypothesis 2 (a) (ii)

The hypothesis under test was that there were no significant muscle activity or gait pattern response differences between unloaded backward walking and two handed pulling.

Significant muscle activity differences (in four out of eight combinations) lead to the rejection of the hypothesis in this regard such that two handed pulling led to significant differences in muscle activity as compared to unloaded backward walking.

With regards to two handed pulling effects on gait responses, no significant differences were found between control and experimental conditions. This led to the conclusion that the majority of backward walking gait responses support the null hypothesis and thus it is tentatively retained in this instance.

Psychophysical hypothesis

Hypothesis 3

The hypothesis tested here suggested that body discomfort ratings were not significantly affected by load/technique combinations. In this case the null hypothesis is tentatively retained although the subjective nature of the responses complicates the full assessment of this hypothesis.

CONCLUSIONS

Effect of load on biomechanical and psychophysical responses

Load mass played a significant role in determining hand force requirement during all three motion phases. Average increases in force requirement (from 250kg to 500kg load) ranged between 30% and 77% with the highest increases occurring in the sustained phase. Furthermore the introduction of a 250kg load to backward and forward walking (by pushing/pulling a load) resulted in a significant increase in muscle activation levels for all pushing/pulling techniques. However, further increases in load to 500kg only resulted in an associated increase in muscle activity in 25% of the responses. These findings suggest that although pushing and pulling of loads increases muscle activity above 'normal' levels, this relationship is not a linear one. Regardless of the load, only a certain percentage of the extra muscular effort is provided by the lower extremities. The rest is most likely to be provided by the upper body, highlighting the need for electromyographical analyses of the upper body in future pushing and pulling investigations. Gait pattern responses were not significantly affected by load; even during pushing and pulling of loads up to 500kg, gait pattern responses were not significantly different to unloaded gait responses. Perceptually, increased load led to increased reports of body discomfort, suggesting that load strongly impacted how individuals perceived the pushing/pulling tasks.

Effect of technique on biomechanical and psychophysical responses

It was found that there were overall significant technique effects on biomechanical responses, however these only occurred in several individual cases. During the initial and sustained phases (at 500kg) pushing elicited significantly higher hand forces than either pulling technique, indicating that pushing is least preferable. In the case of muscle activity responses, significant technique effects were found in three of the four observed muscles; although further analysis revealed only two individual differences, in both cases pushing was seen to elicit the lowest muscle activity responses ($p<0.05$). Significant technique effects were identified with regards to gait pattern responses, however post hoc analysis did not identify individual cases of significance. This would indicate that technique may tenuously affect gait pattern parameters, consequently more research is required to elucidate this relationship. From a psychophysical perspective, pushing was the most preferred technique at all loads, while one handed pulling appeared to be preferable over two handed pulling at 250kg. Contrastingly, two handed pulling was preferable over unilateral pulling at 500kg; this concurs with previous research that reports increased use of the two handed technique with increased load mass. From a psychophysical perspective, the calves, biceps and shoulders were cited most often in terms of discomfort, thus indicating potential areas of concern regarding musculoskeletal disorders.

The contradiction between hand force exertion and muscle activity responses whereby pushing elicited the highest hand forces and the lowest muscular activation levels illustrates the lack of correlation between hand force and lower limb muscle activity responses evidenced in the current study. This would support the proposal that hand forces may not necessarily be indicative of the physical demand placed on the individual (Hoozemans **et al.**, 2004), particularly in the lower extremities. In addition, future studies should investigate both upper and lower body muscle activity together to gain a more holistic concept of the physical demands of a push/pull task and elucidate the mechanisms behind the musculoskeletal demands placed on the body.

Motion phases-impact on force exertion

The three motion phases (initial, sustained and ending) are generally agreed to place differing demands on individuals; the initial phase has been identified as that requiring the highest hand force exertion and consequently most likely to result in over exertion. The current results concur with this finding as significantly greater hand forces were exerted in the initial phase as compared to the sustained and ending phases. Furthermore, at 500kg all three techniques elicited hand forces higher than recommended acceptable guidelines and these are of concern with respect to potential musculoskeletal injury.

Research indicates that the relationship between load and initial hand force is linear, however this relationship is context specific. Results from the present study imply that hand forces are affected by more than just the load mass moved; further factors such as frictional force are integral in determining the relationship between load and exerted forces. When making recommendations to industry, Ergonomists need to ensure that they are applicable to the specific context and are not generalised from seemingly similar circumstances; each workplace needs to be considered in isolation. This relationship remains advantageous as it allows for extrapolation of hand forces from lower loads to higher ones, if the specific relationship is known for a certain situation.

Conclusion

Load played a key role in determining task demands and had a significant impact on hand force exertion while leading to increased muscle activation when compared to unloaded muscle activity responses. Gait responses were not discernibly affected by load movement and thus do not appear to be responsible for increased risk of slip, trip and fall incidents reported during pushing and pulling. Some significant technique effects were found; these indicated that pushing elicited the highest hand forces, while the remaining responses reflected the fact that pushing placed the lowest demand on the musculoskeletal system. It is important here to acknowledge the role played by posture; higher hand forces may not necessarily indicate a less preferable technique as this is indeed likely to be posture dependent. The importance of adopting a holistic integrated approach is evident from these results. The disparity between certain responses indicates that determination of physical demands incurred during pushing/pulling is both complex and multifaceted. Furthermore Hoozemans **et al.** (2004) argue that the relationship between hand forces and musculoskeletal injury is tenuous at best. Consequently, despite higher hand forces, the majority of the responses advocate the use of pushing rather than pulling. This was furthermore the case at both lower and higher loads. While the differences between the pulling techniques is more ambiguous, it would appear that lower loads favour the use of unilateral above two handed pulling. Increasing task demands would require the adoption of a symmetrical pulling technique as one handed pulling becomes increasingly inappropriate and more likely to lead to the risk of musculoskeletal disorders.

RECOMMENDATIONS

Future investigations into the effect of load/technique combinations should take the following recommendations into account:

1. Investigation of a greater range of force requirements are important in future as industry evidences a wide range of potential force requirements in the form of various loads, wheel/floor friction and trolley maintenance levels. This would additionally help to validate the linear relationship found between load and hand forces in previous studies.

2. Although hand forces have been widely used to indicate the physical demands placed on workers during pushing and pulling tasks, the lack of consistency between this and other responses (such as muscle activity) suggests that these may not be as indicative as previously thought. The proposal by Hoozemans **et al.** (2004) that aspects such as posture and movement are of greater importance when defining task demands is supported by these findings. Therefore, in future studies, factors such as posture and movement should be investigated to allow for a greater understanding.

3. Quantification of muscle activity in the upper body during push/pull tasks is recommended as a means of gaining clarity regarding possible musculoskeletal strain. The lack of load or push/pull effects on lower limb muscle activity despite increased exerted force exertion indicates that increased a concomitant rise in upper body muscle activity is possible.

4. Investigation of muscle activity would be complimented by investigation of energy expenditure during pushing/pulling. Observation of physiological responses would furthermore enhance the holistic consideration of the demands of dynamic pushing and pulling tasks.

5. When considering potential physiological demands during pushing/pulling, it would be important to consider the fact that workers often perform repetitive, high frequency push/pull tasks throughout the workday. Thus investigation into the influence of walking speed and frequency should be considered by future studies.

6. While gait pattern responses were not significantly affected by pushing/pulling, it is knows that these tasks increase the risk of slipping and falling. To further expound this relationship, and determine the mechanisms behind associated slip accidents, it would be important to consider posture and centre of mass deviation as a complement to gait pattern investigation. In addition gait kinematic and kinetic parameters should also be considered within this framework.

7. It is suggested that future studies consider the effect of pushing/pulling on the spine; the forward flexion during two handed pulling and the twisting evidenced when pulling unilaterally are likely to lead to injuries of the spine. Quantification of these risk factors requires further research and would lead to an increasingly holistic understanding of push/pull tasks.

The following recommendations with regards to dynamic pushing and pulling tasks are suggested:

1. Pushing appears to be the most preferable means of moving a load using a manual handling device as, although it returns the highest hand forces, it is the most desirable from the majority of other biomechanical and perceptual perspectives. This is the case for both lighter and heavier loads. Furthermore the assertion that hand forces may be a poor indicator of musculoskeletal load supports the recommendation of pushing as the most appropriate means of moving a wheeled device.

2. If it is not possible to employ pushing as a technique (as may occur when the visual field is obscured by the load), one handed pulling may be utilised at lower loads as it allows for forward vision. However as loads increase, the impact on the musculoskeletal system results in two handed pulling being recommended at higher loads.

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APPENDICES

APPENDIX A: GENERAL INFORMATION

Experiment schedule
Letter of information to Subject
Subject informed Consent

EXPERIMENT SCHEDULE

Session 1: Habituation

- Welcome and introduction, hand out letters of information and allow them time to read.
- Introduction to the research, experimental conditions and equipment.
- Questions.
- Informed consent forms.
- Explanation of perceptual scale.
- Demographic and anthropometric measures.
- Subject habituation to work shoes, pallet jack and walkway with particular concern to walking speed and technique. Ensure acceleration/deceleration technique is appropriate.
- Allocation of data collection session.

Session 2: Data collection

- Welcome, questions and reminder of perceptual scale.
- Preparation of electrode sites.
- Placement of electrodes, connect to ME6000 and perform of maximal voluntary contractions.
- Subject to put on work boots, connect to DataLOG W4X8 Bluetooth™.
- Perform normal, unloaded walking conditions (control conditions).
- Perform 6 randomised experimental conditions with rest breaks between trials and between conditions.

RHODES UNIVERSITY
DEPARTMENT OF HUMAN KINETICS AND ERGONOMICS
LETTER OF INFORMATION

Dear

Thank you for agreeing to participate as a subject in my Masters research project entitled: **'The effect of load and technique on biomechanical and psychophysical responses to level dynamic pushing and pulling'**.

The aim of the project is to assess biomechanical and perceptual responses at two different loads and three push/pull techniques during a dynamic pushing and pulling task, using a pallet jack similar to those found within industry. Pushing/pulling requires workers to walk backwards and forwards, and although research has shown differences in gait and muscle activity during backward and forward walking, this has yet to be applied to push/pull situations. Pushing/pulling has also been linked to slip, trip and fall accidents and the quantification of gait pattern changes may aid in understanding of these mechanisms. To date there remains little information with regard to this field and thus this research will be important in establishing quantitative data.

It is critically important that you be free of any injuries and illnesses at the time of testing as these may affect the validity of the results. Of particular concern are injuries to the lower limbs that would affect your gait patterns and back problems that would be aggravated by the testing, so please be open and honest about any injuries/illnesses prior to, and during, testing. Prior to any data collection, the procedures will be fully explained to you and you will be free to ask questions at any time if you so wish. Once you have signed the informed consent you will be given an opportunity to habituate yourself to the testing procedures.

You will be required to come to the Human Kinetics and Ergonomics Department on two separate occasions. The first session will be a brief introduction, during which the protocol will be explained to you and I will answer any questions that may arise. I will require some anthropometric data which will include your stature, mass, elbow and shoulder heights and shoe size. Furthermore I will ask you to practice pushing and pulling the trolley walking at a controlled speed so that you become familiar with this and the walkway that the test will take place on. I will ask you to wear the shoes that will be provided during testing to ensure that you are comfortable during the experimentation. The second session will involve actual data collection where I will ask you to perform six conditions, and this session will last approximately ninety minutes. You will be asked to perform three viable trials at each condition, with breaks in between. Furthermore you will be required to perform two control conditions whereby you will not be moving a load, but simply walking as normally as possible.

One of the main aims of this project is to quantify gait responses to various conditions; for this you will be required to wear a pair of flat soled shoes that will be provided in your shoe size. These shoes will have gait sensors attached to the soles of both shoes, and you are asked to wear socks during testing for hygiene purposes. The project is furthermore concerned with muscle use in the lower limb and so we will be required to connect adhesive surface electromyographic (EMG) sensors to your skin. To aid in the accuracy of collection of these results, I will be required to prepare small areas on your right leg (approximately on the areas of the hamstrings, quadriceps, calves and shin) by shaving and cleaning the area. Whilst performing the tasks you will be exerting forces on a Chatillon load cell in place of the handle, and this provides feedback on the forces being applied to the pallet jack.

Perceptual data (how you feel) will be collected after each condition, using the body discomfort scale. This scale will be explained to you in detail.

While I am unable to provide you with feedback directly after the testing session, at the completion of the project we will provide you with feedback if you are interested.Thank you for showing interest in this study. I hope you will benefit from the knowledge gained in this experience. If you have further questions please do not hesitate to ask.
Yours faithfully,

Anthea Bennett
(Human Kinetics and Ergonomics Master of Science student)

RHODES UNIVERSITY
DEPARTMENT OF HUMAN KINETICS AND ERGONOMICS
SUBJECT INFORMED CONSENT FORM

I, ________________________________ having been fully informed of the nature of the research entitled: **'The effect of load and technique on biomechanical and psychophysical responses to level dynamic pushing and pulling'** do hereby give my consent to act as a subject in the above named research project.

I am fully aware of the procedures involved, as well as the potential risks and benefits associated with my participation, as explained to me verbally and in writing. In agreeing to participate in this study, I waive any legal recourse against the researcher or Rhodes University, in the event of any personal injuries sustained. This waiver shall be binding upon my heirs and legal representatives. I realize the necessity to promptly report to the researcher any signs or symptoms indicating any abnormality or distress and I am fully aware that I may withdraw from participation in the study 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 that may have occurred have been answered to my satisfaction.

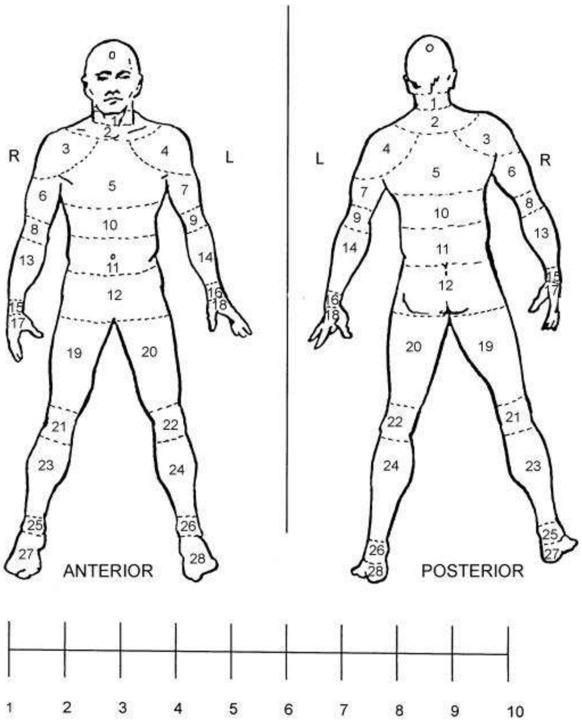
____________________	____________________	____________________
PARTICIPANT (Print name)	(Signed)	(Date)
____________________	____________________	____________________
RESEARCHER (Print name)	(Signed)	(Date)
____________________	____________________	____________________
WITNESS (Print name)	(Signed)	(Date)

APPENDIX B: DATA COLLECTION

Body Discomfort Scale
Instructions to Subject for Body Discomfort
Subject Demographic and Anthropometric Data Sheet
Randomisation of Subjects: permutations
Data Collection Checklist
Data Collection Sheet

BODY DISCOMFORT MAP AND RATING SCALE

(Adapted from Corlett and Bishop, 1986)



BODY DISCOMFORT MAP AND RATING SCALE

Instructions to Subject for Body discomfort

I would like you to determine the location of any discomfort that you experienced while performing the pushing/pulling tasks. You will be required to point to the part(s) of the body discomfort map presented at the locations that correspond to where you felt any discomfort. This map has been divided into the front and back of the body and divided into numbered segments. Ensure that you make it clear which segment you think best describes the location of discomfort, and whether it was on the front or back of your body. You may rate up to 3 sites, however if you felt no discomfort, then indicate this-you are not forced to indicate discomfort if you did not feel any. You will then be asked to rate the intensity of discomfort on a scale of 1 to 10 where 1 refers to “very minimal discomfort” and 10 refers to “extreme discomfort”.

Please try to rate this as honestly and objectively as possible. It is a measure of your perception of the discomfort experienced by the task and gives me an indication of how acceptable you felt the push/pull task to be. In order for this to be accurately reflected, I urge you to be as honest as possible.

SUBJECT DEMOGRAPHIC AND ANTHROPOMETRIC DATA SHEET

Name (for record purposes only)	
Code	
Age (years)	
Stature (mm)	
Mass (kg)	
Shoe size	
Elbow height (mm)	
Shoulder height (mm)	
Right/Left hand dominant	
Condition sequence	

Comments____

RANDOMISATION OF SUBJECTS: PERMUTATIONS

Subject	Conditions (1-6)					
1	1	2	3	4	5	6
2	1	2	5	4	3	6
3	1	4	3	2	5	6
4	1	4	5	2	3	6
5	1	6	3	2	5	4
6	1	6	5	2	3	4
7	2	1	4	3	6	5
8	2	1	6	3	4	5
9	2	3	4	1	6	5
10	2	3	6	1	4	5
11	2	5	4	1	6	3
12	2	5	6	1	4	3
13	3	2	1	6	5	4
14	3	2	5	6	1	4
15	3	4	1	6	5	2
16	3	4	5	6	1	2
17	3	6	1	4	5	2
18	3	6	5	4	1	2
19	4	1	2	3	6	5
20	4	1	6	3	2	5
21	4	3	2	5	6	1
22	4	3	6	5	2	1
23	4	5	2	1	6	3
24	4	5	6	1	2	3
25	5	2	1	6	3	4
26	5	2	3	6	1	4
27	5	4	1	2	3	6
28	5	4	3	2	1	6
29	5	6	1	4	3	2
30	5	6	3	4	1	2
31	6	1	2	5	4	3
32	6	1	4	5	2	3
33	6	3	2	5	4	1
34	6	3	4	5	2	1
35	6	5	2	3	4	1
36	6	5	4	3	2	1

DATA COLLECTION CHECKLIST

Pre-subject arrival

- Check LEDs to ensure they are working correctly.
- Ensure data collection sheets are put out for assistants.
- Ensure all computers on and functioning correctly.

On subject arrival

- Invite participant to sit, explain procedures and equipment again, especially BD scale.
- Shave and prepare areas for electrodes, rub with alcohol.
- Apply electrodes.
- Attach cables to ME6000 and tape down if necessary.
- Ensure that EMG is working and collecting data.
- Perform MVCs: RF, BF, MG and TA in that order.
- Get subject to put on work shoes and walk around. Ensure cables are strapped down and comfortable and that they are able to move freely.

Testing

- Ensure subject is comfortable and in correct starting position with the right foot placed posteriorly.
- Start, ensure assistants mark EMG and gait pattern data.
- Count number of steps and record on data sheet.
- 1 minute rest between trials while pallet jack is being turned around.
- At end of condition BD needs to be taken by research assistant.
- Change loads according to condition.

DATA COLLECTION SHEET
GAIT AND WALKING VELOCITY DATA

Condition____________________

			Number of steps	Speed (st.sec^{-1})	Speed (m.s^{-1})
Time (start and stop)		Trial			
		1			
		2			
		3			
		4			
		5			

Body discomfort	
Site	Rating

Comments____

____

____

EMG DATA

Condition____________________________

		Start		Stop	
Trial	Trial acceptable	Time	Marker	Time	Marker
1					
2					
3					
4					
5					

Comments____

____

____

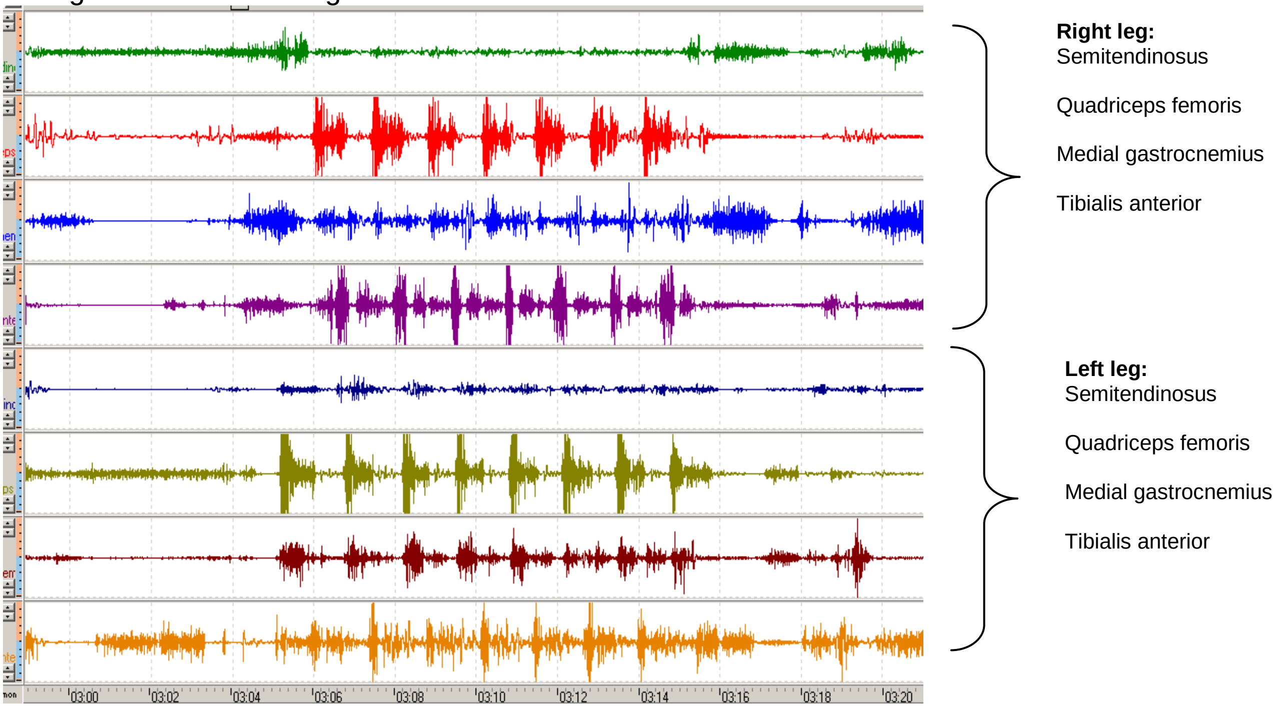
APPENDIX C: ELECTROMYOGRAPHY AND STATISTICAL ANALYSES

Raw EMG tracing examples from pilot studies
MVC Protocols
ANOVA tables: statistical treatments

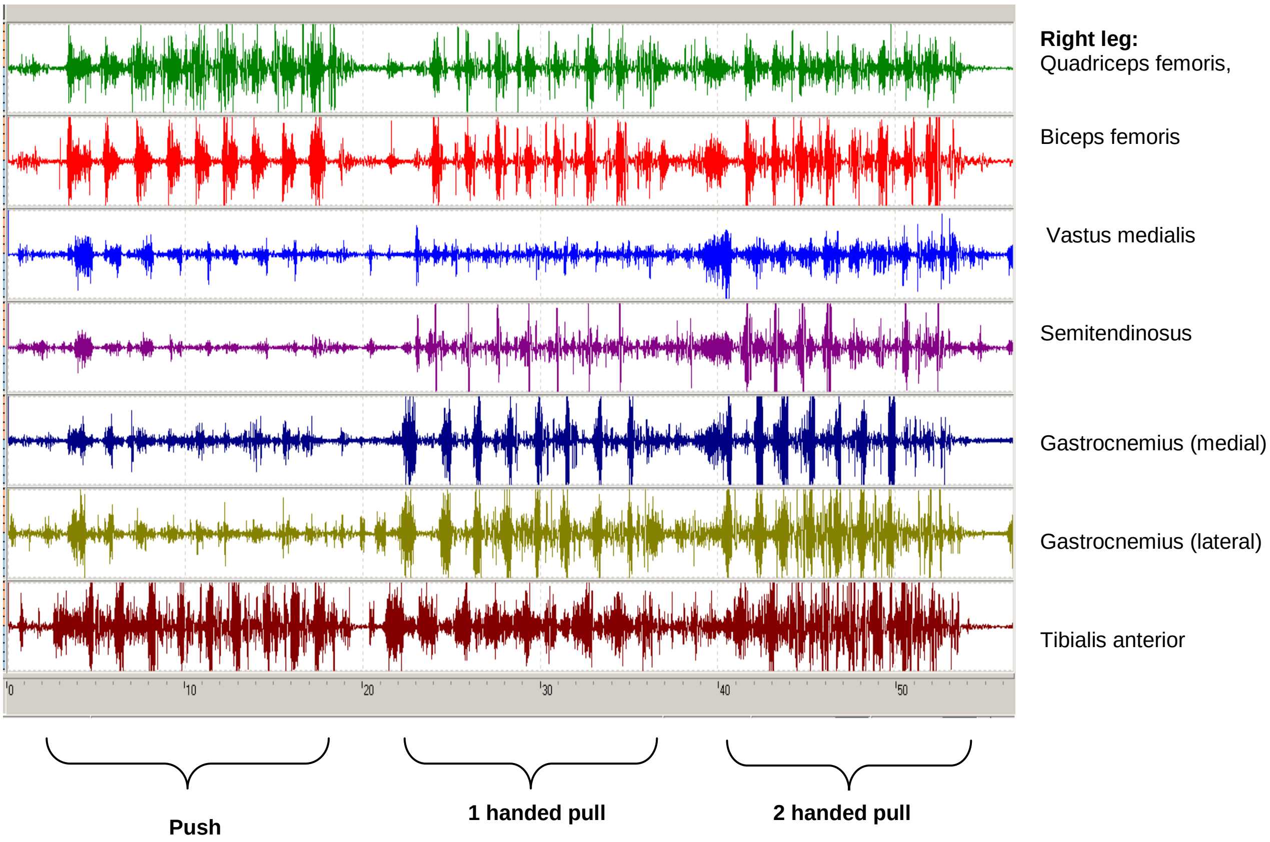
Raw EMG tracing examples from pilot studies

Prior to pilot studies, a thorough review of the related literature revealed a number of muscles that are commonly investigated within gait studies. To a large degree these informed the choice of muscles chosen for the pilot studies.

To determine whether data was to be collected on either one or both legs, the consistency of responses between right and left legs were examined. In this case the semitendinosus, quadriceps femoris, medial gastrocnemius and tibialis anterior muscles were observed on the right and left legs. This was performed on three pilot subjects, and an example is shown below, taken during a pushing trial at 500kg. Responses were seen to be similar in corresponding muscles in the legs, leading to the investigation of muscles in a single leg during the current investigation.

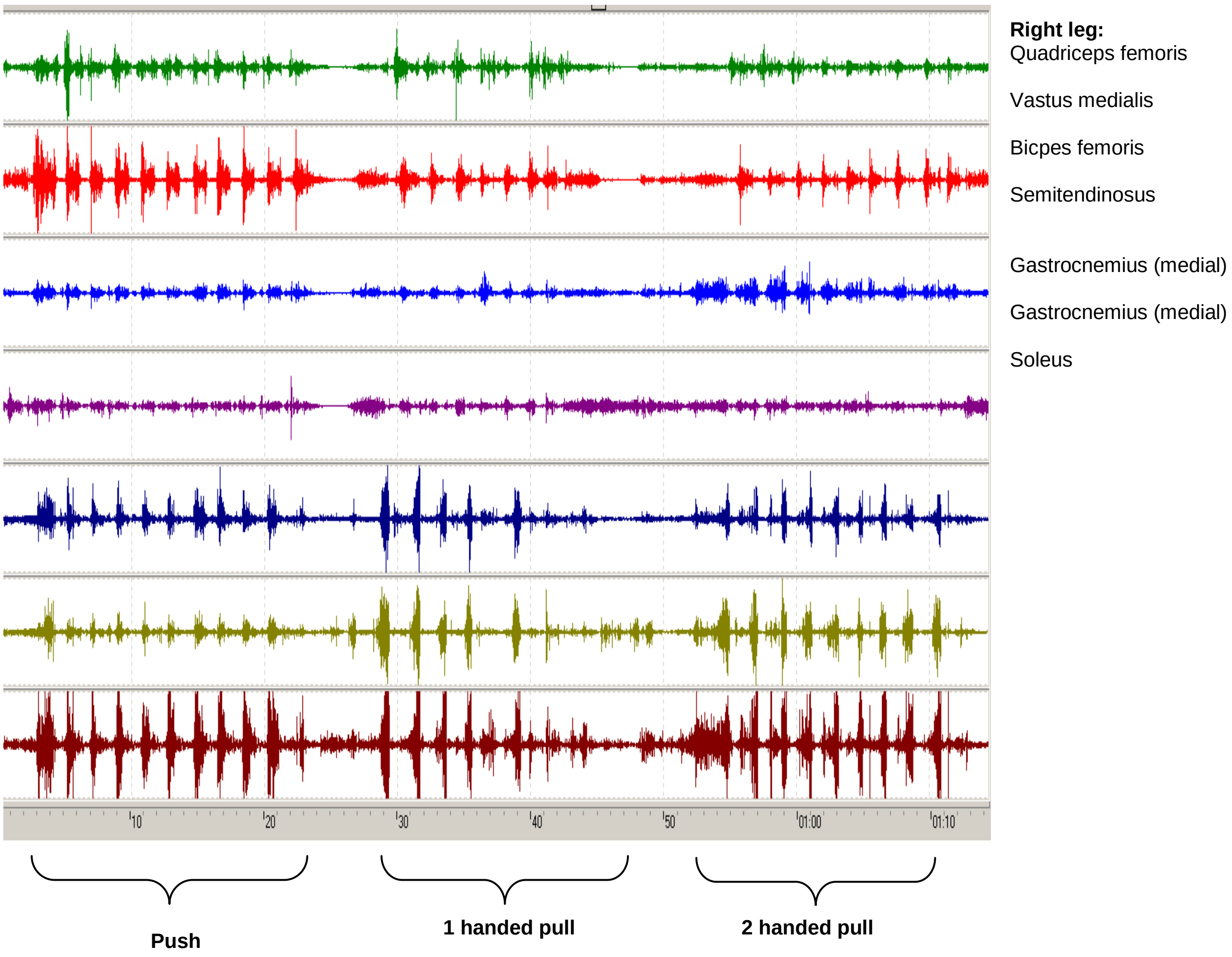


When determining which muscles in the lower extremities were to be investigated, pilot studies aided in determining the responses of a variety of different muscles. In the example below, the quadriceps femoris, vastus medialis, biceps femoris, semitendinosus, gastrocnemius (medial and lateral) and tibialis anterior were observed during pushing, one and two handed pulling at 500kg.



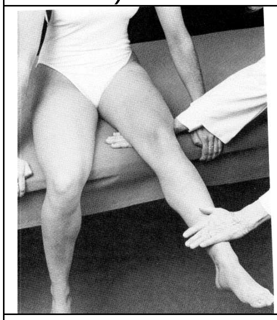
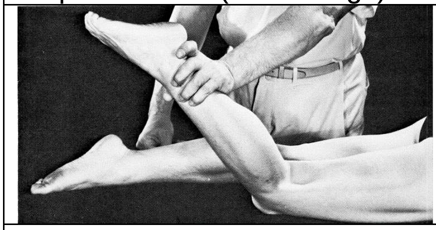
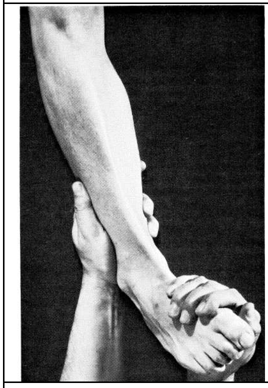
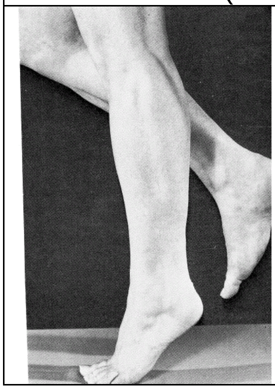
Of these, the greatest responses were seen in the quadriceps femoris, biceps femoris, and tibialis anterior. Activity in the gastrocnemius muscles was similar, thus either could be chosen.

A further pilot study on two individuals examined similar muscles, but additionally considered soleus as an alternative dorsiflexor to the gastrocnemius. An example from this pilot trial is shown below for pushing, one handed and two handed pulling at 500kg. This helped to illustrate the vast differences in muscle activity responses; the trials were conducted with identical protocols, but muscle activity magnitudes and phasic patterns were clearly different.



Results from these pilot investigations suggested that the responses in gastrocnemius and soleus were similar. To determine which of these was to be used in the current study, the issue of accessibility was considered. In this case, the gastrocnemius muscles are superficial to the soleus, thus it was expected that these would be less affected by cross talk. The final muscles determined to be of interest in the current study represented the four major muscle groups of the lower limb and comprised rectus femoris, biceps femoris, medial gastrocnemius and tibialis anterior.

MAXIMAL VOLUNTARY CONTRACTION PROTOCOL (Kendall **et al.**, 1993)

Rectus femoris (Quadrceps femoris)	
	Subject sits with knees over the edge of the table. Pressure is placed against the leg, proximal to the ankle in the direction of knee flexion.
Bicpes femoris (Hamstrings)	
	The subject lies prone; knee is flexed less than 90^0, thigh in slight lateral rotation. Pressure is placed against the leg, proximal to the ankle in the direction of knee extension. No pressure placed against the rotation component.
Tibialis anterior	
	Ankle is dorsiflexed and inverted. Pressure is placed against the medial side of the foot, in the direction of planterflexion of the ankle joint and eversion of the foot.
Gastrocnemius (Medial)	
	Subject is standing, may steady themselves with hand but no weight on hand. Subject rises on toes, pushing body weight directly upwards.

ANOVA TABLES: STATISTICAL TREATMENTS
HAND FORCES: 2 WAY ANOVAs

Univariate Tests of Significance for initial (2 way anova set up) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	14131211	1	14131211	6208.462	0.000000
Load	654500	1	654500	287.551	**0.000000**
Technique	20047	2	10024	4.404	**0.013381**
Load*Technique	8700	2	4350	1.911	0.150459
Error	477985	210	2276		

Tukey HSD test; variable initial (2 way anova set up) Approximate Probabilities for Post Hoc Tests Error: Between MS = 2276.1, df = 210.00

	Load	Technique	{1} - 204.86	{2} - 194.83	{3} - 202.50	{4} - 332.86	{5} - 297.06	{6} - 302.56
1	250kg	Push		0.948616	0.999944	**0.000020**	**0.000020**	**0.000020**
2	250kg	1 H pull	0.948616		0.984003	**0.000020**	**0.000020**	**0.000020**
3	250kg	2 H pull	0.999944	0.984003		**0.000020**	**0.000020**	**0.000020**
4	500kg	Push	**0.000020**	**0.000020**	**0.000020**		**0.018194**	0.076183
5	500kg	1 H pull	**0.000020**	**0.000020**	**0.000020**	**0.018194**		0.996565
6	500kg	2 H pull	**0.000020**	**0.000020**	**0.000020**	0.076183	0.996565	

Univariate Tests of Significance for Sustained (2 way anova set up) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	1271287	1	1271287	5497.886	0.000000
Load	206462	1	206462	892.876	**0.000000**
Technique	3761	2	1880	8.132	**0.000397**
Load*Technique	980	2	490	2.118	0.122802
Error	48559	210	231		

Tukey HSD test; variable Sustained (2 way anova set up) Approximate Probabilities for Post Hoc Tests Error: Between MS = 231.23, df = 210.00

	Load	Technique	{1} - 48.833	{2} - 43.650	{3} - 44.919	{4} - 116.40	{5} - 104.23	{6} - 102.28
1	250kg	Push		0.698595	0.884794	**0.000020**	**0.000020**	**0.000020**
2	250kg	1 H pull	0.698595		0.999272	**0.000020**	**0.000020**	**0.000020**
3	250kg	2 H pull	0.884794	0.999272		**0.000020**	**0.000020**	**0.000020**
4	500kg	Push	**0.000020**	**0.000020**	**0.000020**		**0.008954**	**0.001162**
5	500kg	1 H pull	**0.000020**	**0.000020**	**0.000020**	**0.008954**		0.994404
6	500kg	2 H pull	**0.000020**	**0.000020**	**0.000020**	**0.001162**	0.994404	

Univariate Tests of Significance for ending (2 way anova set up) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	3285575	1	3285575	1232.857	0.000000
Load	100264	1	100264	37.622	**0.000000**
Technique	7661	2	3831	1.437	0.239882
Load*Technique	555	2	277	0.104	0.901241
Error	559652	210	2665		

Tukey HSD test; variable ending (2 way anova set up) Approximate Probabilities for Post Hoc Tests Error: Between MS = 2665.0, df = 210.00

	Load	Technique	{1} - 100.96	{2} - 96.725	{3} - 107.68	{4} - 141.33	{5} - 138.04	{6} - 155.26
1	250kg	Push		0.999328	0.993955	**0.011707**	**0.028015**	**0.000134**
2	250kg	1 H pull	0.999328		0.946632	**0.003366**	**0.008985**	**0.000041**
3	250kg	2 H pull	0.993955	0.946632		**0.000020**	**0.000020**	**0.001298**
4	500kg	Push	**0.011707**	**0.003366**	**0.000020**		0.999804	0.862570
5	500kg	1 H pull	**0.028015**	**0.008985**	**0.000020**	0.999804		0.717436
6	500kg	2 H pull	**0.000134**	**0.000041**	**0.001298**	0.862570	0.717436	

MOTION PHASES: 1 WAY ANOVAs

Univariate Tests of Significance for Var2 (INIT, SUS, ENDING) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	14960116	1	14960116	4618.811	**0.00**
Phase	3727958	2	1863979	575.488	**0.00**
Error	2089125	645	3239		

Tukey HSD test; variable Var2 (INIT, SUS, ENDING) Approximate Probabilities for Post Hoc Tests Error: Between MS = 3239.0, df = 645.00

	Phase	{1} - 255.78	{2} - 76.718	{3} - 123.33
1	Initial		**0.000022**	**0.000022**
2	Sustained	**0.000022**		**0.000022**
3	Ending	**0.000022**	**0.000022**	

ELECTROMYOGRAPHY: MUSCLE ACTIVITY

STUDENT T-TESTS: CONTROL CONDITIONS

T-test for Dependent Samples (Rectus Femoris) Marked differences are significant at p < .05000

	Mean	Std.Dv.	N	Diff.	Std.Dv. - Diff.	t	df	p
Rec NF	1.858994	0.955166						
Rec NB	2.610634	0.624280	36	-0.751640	0.502423	-8.97619	35	**0.000000**

T-test for Dependent Samples (biceps femoris) Marked differences are significant at p < .05000

	Mean	Std.Dv.	N	Diff.	Std.Dv. - Diff.	t	df	p
NF	2.011946	0.924921						
NB	2.282832	0.779060	36	-0.270885	0.326386	-4.97972	35	**0.000017**

T-test for Dependent Samples (Medial Gastroc) Marked differences are significant at p < .05000

	Mean	Std.Dv.	N	Diff.	Std.Dv. - Diff.	t	df	p
Gastroc NF	2.819037	0.372329						
Gastroc NB	2.796374	0.428469	36	0.022663	0.297902	0.456452	35	0.650885

T-test for Dependent Samples (tibialis anterior) Marked differences are significant at p < .05000

	Mean	Std.Dv.	N	Diff.	Std.Dv. - Diff.	t	df	p
Tib NF	2.734642	0.266279						
Tib NB	3.038132	0.276682	36	-0.303490	0.182844	-9.95899	35	**0.000000**

REPEATED MEASURES ANOVAs: CONTROL VS. EXPERIMENTAL CONDITIONS

Repeated Measures Analysis of Variance (Rectus repeated measure) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	973.6084	1	973.6084	290.8690	**0.00**
Error	117.1534	35	3.3472		
COND	19.5729	4	4.8932	75.4307	**0.00**
Error	9.0819	140	0.0649		

Tukey HSD test; variable DV_1 (Rectus repeated measure) Approximate Probabilities for Post Hoc Tests Error: Within MS = .06487, df = 140.00

	COND	{1} - 1.8590	{2} - 2.0998	{3} - 2.5418	{4} - 2.3246	{5} - 2.8033
1	Rec NF		**0.000588**	**0.000017**	**0.000017**	**0.000017**
2	Rec 1	**0.000588**		**0.000017**	**0.001707**	**0.000017**
3	Rec 2	**0.000017**	**0.000017**		**0.002761**	**0.000142**
4	Rec 5	**0.000017**	**0.001707**	**0.002761**		**0.000017**
5	Rec 6	**0.000017**	**0.000017**	**0.000142**	**0.000017**	

Repeated Measures Analysis of Variance (Rectus repeated measure) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	841.4838	1	841.4838	1097.836	**0.000000**
Error	26.8273	35	0.7665		
COND	2.9124	2	1.4562	23.867	**0.000000**
Error	4.2708	70	0.0610		

Tukey HSD test; variable DV_1 (Rectus repeated measure) Approximate Probabilities for Post Hoc Tests Error: Within MS = .06101, df = 70.000

	COND	{1} - 2.6106	{2} - 2.7553	{3} - 3.0080
1	Rec NB		**0.040239**	**0.000111**
2	Rec 3	**0.040239**		**0.000239**
3	Rec 4	**0.000111**	**0.000239**	

Repeated Measures Analysis of Variance (biceps femoris) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	937.0015	1	937.0015	307.2690	**0.00**
Error	106.7307	35	3.0494		
R1	6.9148	4	1.7287	36.0116	**0.00**
Error	6.7205	140	0.0480		

Tukey HSD test; variable DV_1 (biceps femoris) Approximate Probabilities for Post Hoc Tests Error: Within MS = .04800, df = 140.00

	R1	{1} - 2.0119	{2} - 2.1335	{3} - 2.3233	{4} - 2.3575	{5} - 2.5815
1	NF		0.128020	**0.000017**	**0.000017**	**0.000017**
2	1	0.128020		**0.002237**	**0.000154**	**0.000017**
3	2	**0.000017**	**0.002237**		0.964353	**0.000022**
4	5	**0.000017**	**0.000154**	0.964353		**0.000154**
5	6	**0.000017**	**0.000017**	**0.000022**	**0.000154**	

Repeated Measures Analysis of Variance (biceps femoris) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	560.3512	1	560.3512	351.7818	**0.000000**
Error	55.7513	35	1.5929		
R1	0.5065	2	0.2533	5.6035	**0.005529**
Error	3.1639	70	0.0452		

Tukey HSD test; variable DV_1 (biceps femoris) Approximate Probabilities for Post Hoc Tests Error: Within MS = .04520, df = 70.000

	R1	{1} - 2.2828	{2} - 2.1915	{3} - 2.3591
1	NB		0.170055	0.287269
2	3	0.170055		**0.003867**
3	4	0.287269	**0.003867**	

Repeated Measures Analysis of Variance (Gastroc repeated measure) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	1717.911	1	1717.911	3005.656	**0.00**
Error	20.005	35	0.572		
COND	5.082	4	1.271	58.393	**0.00**
Error	3.046	140	0.022		

Tukey HSD test; variable DV_1 (Gastroc repeated measure) Approximate Probabilities for Post Hoc Tests Error: Within MS = .02176, df = 140.00

	COND	{1} - 2.8190	{2} - 3.0122	{3} - 3.2203	{4} - 3.0936	{5} - 3.3015
1	Gastroc NF		**0.000017**	**0.000017**	**0.000017**	**0.000017**
2	Gastroc 1	**0.000017**		**0.000017**	0.132111	**0.000017**
3	Gastroc 2	**0.000017**	**0.000017**		**0.002529**	0.133410
4	Gastroc 5	**0.000017**	0.132111	**0.002529**		**0.000017**
5	Gastroc 6	**0.000017**	**0.000017**	0.133410	**0.000017**	

Repeated Measures Analysis of Variance (Gastroc repeated measure) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	922.6264	1	922.6264	1411.647	**0.000000**
Error	22.8754	35	0.6536		
COND	2.3582	2	1.1791	41.485	**0.000000**
Error	1.9895	70	0.0284		

Tukey HSD test; variable DV_1 (Gastroc repeated measure) Approximate Probabilities for Post Hoc Tests Error: Within MS = .02842, df = 70.000

	COND	{1} - 2.7964	{2} - 2.8419	{3} - 3.1301
1	Gastroc NB		0.488979	**0.000111**
2	Gastroc 3	0.488979		**0.000111**
3	Gastroc 4	**0.000111**	**0.000111**	

Repeated Measures Analysis of Variance (tibialis anterior) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	1580.218	1	1580.218	4692.612	**0.00**
Error	11.786	35	0.337		
COND	6.775	4	1.694	97.419	**0.00**
Error	2.434	140	0.017		

Tukey HSD test; variable DV_1 (tibialis anterior) Approximate Probabilities for Post Hoc Tests Error: Within MS = .01738, df = 140.00

	COND	**{1} - 2.7346**	**{2} - 2.8076**	**{3} - 3.1406**	**{4} - 2.8940**	**{5} - 3.2379**
1	Tib NF		0.130498	**0.000017**	**0.000020**	**0.000017**
2	Tib 1	0.130498		**0.000017**	**0.043154**	**0.000017**
3	Tib 2	**0.000017**	**0.000017**		**0.000017**	**0.015050**
4	Tib 5	**0.000020**	**0.043154**	**0.000017**		**0.000017**
5	Tib 6	**0.000017**	**0.000017**	**0.015050**	**0.000017**	

Repeated Measures Analysis of Variance (tibialis anterior) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	**Degr. of - Freedom**	**MS**	**F**	**p**
Intercept	1020.854	1	1020.854	4643.111	**0.000000**
Error	7.695	35	0.220		
COND	0.215	2	0.108	7.762	**0.000902**
Error	0.971	70	0.014		

Tukey HSD test; variable DV_1 (tibialis repeated measure) Approximate Probabilities for Post Hoc Tests Error: Within MS = .01387, df = 70.000

	COND	**{1} - 3.0381**	**{2} - 3.0479**	**{3} - 3.1374**
1	Tib NB		0.934100	**0.001926**
2	Tib 3	0.934100		**0.005515**
3	Tib 4	**0.001926**	**0.005515**	

EXPERIMENTAL CONDITIONS: 2 WAY ANOVAs

Univariate Tests of Significance for Rectus MA (2 way anova set up) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	**Degr. of - Freedom**	**MS**	**F**	**p**
Intercept	1447.629	1	1447.629	2720.111	**0.000000**
Load	8.262	1	8.262	15.524	**0.000111**
Technique	11.391	2	5.695	10.702	**0.000038**
Load*Technique	0.530	2	0.265	0.498	0.608565
Error	111.761	210	0.532		

Tukey HSD test; variable Rectus MA (2 way anova set up) Approximate Probabilities for Post Hoc Tests Error: Between MS = .53220, df = 210.00

	Load	**Technique**	**{1} - 2.0998**	**{2} - 2.3246**	**{3} - 2.7553**	**{4} - 2.5418**	**{5} - 2.8033**	**{6} - 3.0080**
1	250kg	Push		0.781291	**0.001919**	0.104564	**0.000622**	**0.000022**
2	250kg	1 H pull	0.781291		0.122467	0.804984	0.059955	**0.001004**
3	250kg	2 H pull	**0.001919**	0.122467		0.816257	0.999773	0.683868
4	500kg	Push	0.104564	0.804984	0.816257		0.650686	0.072994
5	500kg	1 H pull	**0.000622**	0.059955	0.999773	0.650686		0.841742
6	500kg	2 H pull	**0.000022**	**0.001004**	0.683868	0.072994	0.841742	

Univariate Tests of Significance for Bicpes MA (2 way anova set up) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	**Degr. of - Freedom**	**MS**	**F**	**p**
Intercept	1167.032	1	1167.032	2022.386	**0.000000**
Load	2.027	1	2.027	3.513	0.062274
Technique	2.353	2	1.176	2.039	0.132782
Load*Technique	0.029	2	0.015	0.025	0.975122
Error	121.182	210	0.577		

Tukey HSD test; variable Bicpes MA (2 way anova set up) Approximate Probabilities for Post Hoc Tests Error: Between MS = .57706, df = 210.00

	Load	Technique	{1} - 2.1335	{2} - 2.3575	{3} - 2.1915	{4} - 2.3233	{5} - 2.5815	{6} - 2.3591
1	250kg	Push		0.811476	0.999529	0.897162	0.123451	0.807007
2	250kg	1 H pull	0.811476		0.939658	0.999965	0.811599	1.000000
3	250kg	2 H pull	0.999529	0.939658		0.977485	0.248060	0.937346
4	500kg	Push	0.897162	0.999965	0.977485		0.701322	0.999957
5	500kg	1 H pull	0.123451	0.811599	0.248060	0.701322		0.816017
6	500kg	2 H pull	0.807007	1.000000	0.937346	0.999957	0.816017	

Univariate Tests of Significance for Gastroc MA (2 way anova set up) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	2075.687	1	2075.687	11897.23	**0.000000**
Load	2.974	1	2.974	17.05	**0.000053**
Technique	1.639	2	0.820	4.70	**0.010089**
Load*Technique	0.077	2	0.039	0.22	0.801589
Error	36.638	210	0.174		

Tukey HSD test; variable Gastroc MA (2 way anova set up) Approximate Probabilities for Post Hoc Tests Error: Between MS = .17447, df = 210.00

	Load	Technique	{1} - 3.0122	{2} - 3.0936	{3} - 2.8419	{4} - 3.2203	{5} - 3.3015	{6} - 3.1301
1	250kg	Push		0.962686	0.511941	0.280392	**0.038793**	0.838293
2	250kg	1 H pull	0.962686		0.108248	0.792718	0.281179	0.999091
3	250kg	2 H pull	0.511941	0.108248		**0.001703**	**0.000062**	**0.040053**
4	500kg	Push	0.280392	0.792718	**0.001703**		0.962979	0.942702
5	500kg	1 H pull	**0.038793**	0.281179	**0.000062**	0.962979		0.504683
6	500kg	2 H pull	0.838293	0.999091	**0.040053**	0.942702	0.504683	

Univariate Tests of Significance for Tibialis MA (2 way anova set up) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	2001.728	1	2001.728	23715.47	**0.000000**
Load	3.524	1	3.524	41.75	**0.000000**
Technique	0.557	2	0.278	3.30	**0.038838**
Load*Technique	0.745	2	0.373	4.41	**0.013246**
Error	17.725	210	0.084		

Tukey HSD test; variable Tibialis MA (2 way anova set up) Approximate Probabilities for Post Hoc Tests Error: Between MS = .08441, df = 210.00

	Load	Technique	{1} - 2.8076	{2} - 2.8940	{3} - 3.0479	{4} - 3.1406	{5} - 3.2379	{6} - 3.1374
1	250kg	Push		0.805694	**0.005996**	**0.000036**	**0.000020**	**0.000040**
2	250kg	1 H pull	0.805694		0.215974	**0.004300**	**0.000027**	**0.005110**
3	250kg	2 H pull	**0.005996**	0.215974		0.754719	0.061615	0.781685
4	500kg	Push	**0.000036**	**0.004300**	0.754719		0.714437	1.000000
5	500kg	1 H pull	**0.000020**	**0.000027**	**0.061615**	0.714437		0.684801
6	500kg	2 H pull	**0.000040**	**0.005110**	0.781685	1.000000	0.684801	

GAIT RESPONSES

STUDENT T-TESTS: CONTROL CONDITIONS

T-test for Dependent Samples (Duration) Marked differences are significant at p < .05000

	Mean	**Std.Dv.**	**N**	**Diff.**	**Std.Dv. - Diff.**	**t**	**df**	**p**
NF	1.427188	0.081443						
NB	1.399186	0.102302	30	0.028001	0.090733	1.690337	29	0.101687

T-test for Dependent Samples (Right foot contact) Marked differences are significant at p < .05000

	Mean	**Std.Dv.**	**N**	**Diff.**	**Std.Dv. - Diff.**	**t**	**df**	**p**
NF	74.66993	4.342231						
NB	72.39991	5.210508	30	2.270018	6.273387	1.981928	29	0.057036

T-test for Dependent Samples (Left foot contact) Marked differences are significant at p < .05000

	Mean	**Std.Dv.**	**N**	**Diff.**	**Std.Dv. - Diff.**	**t**	**df**	**p**
NF	74.26509	4.363956						
NB	70.10384	4.400357	30	4.161254	6.366542	3.579985	29	**0.001235**

T-test for Dependent Samples (BDS) Marked differences are significant at p < .05000

	Mean	**Std.Dv.**	**N**	**Diff.**	**Std.Dv. - Diff.**	**t**	**df**	**p**
NF	26.15260	8.76665						
NB	25.02498	14.01483	30	1.127618	16.29045	0.379131	29	0.707352

T-test for Dependent Samples (TDS) Marked differences are significant at p < .05000

	Mean	**Std.Dv.**	**N**	**Diff.**	**Std.Dv. - Diff.**	**t**	**df**	**p**
NF	25.17208	4.234155						
NB	22.21262	5.388969	30	2.959461	6.974653	2.324077	29	**0.027331**

T-test for Dependent Samples (SS right) Marked differences are significant at p < .05000

	Mean	**Std.Dv.**	**N**	**Diff.**	**Std.Dv. - Diff.**	**t**	**df**	**p**
NF	30.75059	13.55288						
NB	31.39630	6.72682	30	-0.645715	10.85798	-0.325726	29	0.746970

T-test for Dependent Samples (SS left) Marked differences are significant at p < .05000

	Mean	**Std.Dv.**	**N**	**Diff.**	**Std.Dv. - Diff.**	**t**	**df**	**p**
NF	25.33007	4.342231						
NB	27.60009	5.210508	30	-2.27002	6.273387	-1.98193	29	0.057036

REPEATED MEASURES ANOVAs: CONTROL VS. EXPERIMENTAL CONDITIONS

Repeated Measures Analysis of Variance (duration NF) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	**Degr. of - Freedom**	**MS**	**F**	**p**
Intercept	309.9573	1	309.9573	15943.97	0.000000
Error	0.5638	29	0.0194		
R1	0.1888	4	0.0472	2.57	**0.041824**
Error	2.1334	116	0.0184		

Tukey HSD test; variable DV_1 (duration NF) Approximate Probabilities for Post Hoc Tests Error: Within MS = .01839, df = 116.00

	R1	{1} - 1.4272	{2} - 1.4719	{3} - 1.4724	{4} - 1.3761	{5} - 1.4399
1	NF		0.705668	0.696458	0.590361	0.996363
2	Push (250kg)	0.705668		1.000000	0.054646	0.890452
3	Push (500kg)	0.696458	1.000000		0.052564	0.884500
4	1 H Pull (250kg)	0.590361	0.054646	0.052564		0.366161
5	1 H Pull (500kg)	0.996363	0.890452	0.884500	0.366161	

Repeated Measures Analysis of Variance (duration NB) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	174.6403	1	174.6403	9652.263	0.000000
Error	0.5247	29	0.0181		
R1	0.0232	2	0.0116	0.850	0.432584
Error	0.7902	58	0.0136		

Repeated Measures Analysis of Variance (right foot contact NF) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	833126.7	1	833126.7	8616.756	0.000000
Error	2803.9	29	96.7		
R1	100.8	4	25.2	1.163	0.330759
Error	2512.7	116	21.7		

Repeated Measures Analysis of Variance (right foot contact NB) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	454964.7	1	454964.7	9594.531	0.000000
Error	1327.7	28	47.4		
R1	10.3	2	5.1	0.121	0.886362
Error	2380.1	56	42.5		

Repeated Measures Analysis of Variance (left foot NF) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	821348.4	1	821348.4	10129.25	0.000000
Error	2351.5	29	81.1		
R1	28.4	4	7.1	0.32	0.862447
Error	2553.8	116	22.0		

Repeated Measures Analysis of Variance (repeated measures gait data) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	449679.8	1	449679.8	5611.105	0.000000
Error	2324.1	29	80.1		
R1	79.5	2	39.8	1.341	0.269607
Error	1719.7	58	29.7		

Repeated Measures Analysis of Variance (BDS NF) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	102639.7	1	102639.7	640.2887	0.000000
Error	4648.8	29	160.3		
R1	162.8	4	40.7	0.4307	0.786233
Error	10962.5	116	94.5		

Repeated Measures Analysis of Variance (BDS NB) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	64124.03	1	64124.03	273.0752	0.000000
Error	6809.83	29	234.82		
R1	654.53	2	327.26	2.9672	0.059306
Error	6396.98	58	110.29		

Repeated Measures Analysis of Variance (TDS NF) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	93933.98	1	93933.98	737.0909	0.000000
Error	3695.73	29	127.44		
R1	58.13	4	14.53	0.5948	0.667066
Error	2833.88	116	24.43		

Repeated Measures Analysis of Variance (TDS NB) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	51005.07	1	51005.07	895.4789	0.000000
Error	1651.79	29	56.96		
R1	115.27	2	57.64	1.8444	0.167270
Error	1812.39	58	31.25		

Repeated Measures Analysis of Variance (SS RIGHT NF) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	138039.9	1	138039.9	826.6744	0.000000
Error	4842.5	29	167.0		
R1	479.9	4	120.0	0.9110	0.460047
Error	15276.4	116	131.7		

Repeated Measures Analysis of Variance (SS RIGHT NB) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	89420.69	1	89420.69	708.4555	0.000000
Error	3660.36	29	126.22		
R1	332.91	2	166.45	1.9744	0.148071
Error	4889.80	58	84.31		

Repeated Measures Analysis of Variance (SS LEFT NF) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	97397.75	1	97397.75	934.3770	0.000000
Error	3022.91	29	104.24		
R1	98.40	4	24.60	1.2529	0.292634
Error	2277.65	116	19.63		

Repeated Measures Analysis of Variance (repeated measures gait data) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	67592.07	1	67592.07	1279.195	0.000000
Error	1532.35	29	52.84		
R1	9.18	2	4.59	0.111	0.894697
Error	2388.72	58	41.18		

EXPERIMENTAL CONDITIONS: 2 WAY ANOVAs

Univariate Tests of Significance for duration (2 way anovas gait patterns) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	364.6650	1	364.6650	18045.89	0.000000
Load	0.0035	1	0.0035	0.17	0.677159
Technique	0.2244	2	0.1122	5.55	**0.004600**
Load*Technique	0.0790	2	0.0395	1.95	0.144786
Error	3.5161	174	0.0202		

Tukey HSD test; variable duration (2 way anovas gait patterns) Approximate Probabilities for Post Hoc Tests Error: Between MS = .02021, df = 174.00

	Load	Technique	{1} - 1.4719	{2} - 1.4088	{3} - 1.3761	{4} - 1.4724	{5} - 1.3710	{6} - 1.4399
1	250kg	Push		0.518918	0.094415	1.000000	0.065940	0.952882
2	250kg	1 H pull	0.518918		0.948488	0.509342	0.907955	0.958872
3	250kg	2 H pull	0.094415	0.948488		0.091044	0.999993	0.506405
4	500kg	Push	1.000000	0.509342	0.091044		0.063425	0.949545
5	500kg	1 H pull	0.065940	0.907955	0.999993	0.063425		0.417089
6	500kg	2 H pull	0.952882	0.958872	0.506405	0.949545	0.417089	

Univariate Tests of Significance for foot contact right (2 way anovas gait patterns) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	982605.2	1	982605.2	21676.77	0.000000
Load	33.3	1	33.3	0.73	0.392882
Technique	133.0	2	66.5	1.47	0.233422
Load*Technique	66.6	2	33.3	0.73	0.481373
Error	7887.4	174	45.3		

Univariate Tests of Significance for left foot contact (2 way anovas gait patterns) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	957801.3	1	957801.3	21270.15	0.000000
Load	46.4	1	46.4	1.03	0.311630
Technique	367.5	2	183.7	4.08	**0.018546**
Load*Technique	25.3	2	12.7	0.28	0.755321
Error	7835.3	174	45.0		

Tukey HSD test; variable left foot contact (2 way anovas gait patterns) Approximate Probabilities for Post Hoc Tests Error: Between MS = 45.030, df = 174.00

	Load	Technique	{1} - 74.612	{2} - 73.737	{3} - 72.011	{4} - 74.031	{5} - 73.343	{6} - 69.941
1	250kg	Push		0.996003	0.663672	0.999442	0.977976	0.076020
2	250kg	1 H pull	0.996003		0.919418	0.999981	0.999917	0.241927
3	250kg	2 H pull	0.663672	0.919418		0.853271	0.972772	0.839552
4	500kg	Push	0.999442	0.999981	0.853271		0.998735	0.170367
5	500kg	1 H pull	0.977976	0.999917	0.972772	0.998735		0.363563
6	500kg	2 H pull	0.076020	0.241927	0.839552	0.170367	0.363563	

Univariate Tests of Significance for BDS (2 way anovas gait patterns) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	127507.9	1	127507.9	1061.892	0.000000
Load	37.4	1	37.4	0.311	0.577602
Technique	143.2	2	71.6	0.596	0.552070
Load*Technique	586.3	2	293.2	2.442	0.090005
Error	20893.3	174	120.1		

Univariate Tests of Significance for TDS (2 way anovas gait patterns) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	111237.2	1	111237.2	2242.349	0.000000
Load	22.3	1	22.3	0.449	0.503735
Technique	37.6	2	18.8	0.379	0.685125
Load*Technique	4.4	2	2.2	0.044	0.956636
Error	8631.7	174	49.6		

Univariate Tests of Significance for SS right (2 way anovas gait patterns) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	169454.9	1	169454.9	1338.405	0.000000
Load	341.3	1	341.3	2.696	0.102438
Technique	78.8	2	39.4	0.311	0.732846
Load*Technique	458.5	2	229.3	1.811	0.166584
Error	22030.1	174	126.6		

Univariate Tests of Significance for SS left (2 way anovas gait patterns) Sigma-restricted parameterization Effective hypothesis decomposition

	SS	Degr. of - Freedom	MS	F	p
Intercept	122763.3	1	122763.3	2708.184	0.000000
Load	33.3	1	33.3	0.734	0.392886
Technique	133.0	2	66.5	1.467	0.233455
Load*Technique	66.6	2	33.3	0.734	0.481384
Error	7887.5	174	45.3		