

**THE EFFECT OF LOAD AND TECHNIQUE ON BIOMECHANICAL AND
PERCEPTUAL RESPONSES DURING DYNAMIC PUSHING AND PULLING**

**BY
SHEENA DHIKSHA DESAI**

THESIS

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

**Department of Human Kinetics and Ergonomics
Rhodes University, 2008
Grahamstown, South Africa**

ABSTRACT

Changes in the industrial job profile, from lifting and lowering to repetitive dynamic pushing and pulling have been facilitated through the use of manual vehicles, aimed at minimising the workload. Yet, the demands of pushing and pulling have not been well documented. Using measures of the horizontal component of the hand forces, spinal kinematics, muscle activity at various sites on the upper body and body discomfort ratings, this study aimed at quantifying the biomechanical and perceptual demands of various dynamic push/pull techniques. 36 healthy male participants performed two-handed forward pushing, two-handed backward pulling and one-handed forward pulling, employing an industrial pallet jack supporting two loads of 250kg or 500kg.

While no single technique was definitively identified as preferable regarding hand forces, pushing at 500kg elicited higher initial and sustained forces ($p < 0.05$) than one- and two-handed pulling respectively. Increments in load mass from 250kg to 500kg resulted in significant differences in the initial, sustained and ending forces. With regard to spinal kinematics in the sagittal plane, two-handed pulling elicited the highest trunk flexion, and may therefore expose individuals to prolonged forward bending. Generally this technique was found to evoke the highest sagittal responses. Spinal kinematic measures in the lateral and transverse planes suggested that one-handed pulling was accompanied by the highest measures, and hence the greatest risk of developing lower back disorders related to this plane. Although various combinations of muscles were active during each technique, one-handed pulling and pushing, most often induced the highest muscle activation levels and two-handed pulling, the lowest. While erector spinae evidenced no significant differences between techniques at each load or between loads for the same technique, activation levels were high under all conditions. Perceptual ratings of body discomfort revealed that not only is the upper body susceptible to injuries during pushing and pulling, but also that the lower extremities may have a considerable role to play in these tasks, with the calves being a particular area of concern. Findings concluded that symmetrical pushing and pulling tasks are preferable.

ACKNOWLEDGEMENTS

The following people deserve my acknowledgement and most sincere gratitude for their support throughout the duration of this research:

My supervisor, Andrew Todd, for his patience, encouragement, dedication and unfailing willingness to teach.

My family, whose love, support and encouragement over the years has never faltered.

Rohitesh Dhawan, for always believing in my capabilities and whose endless support and encouragement has been a comfort to me.

Professor Matthias Göbel for his invaluable knowledge, expertise and for challenging my way of thinking.

My colleagues (and friends) Anthea Bennett, Jonathan Davy and Sma Ngcamu, for their support, humour and (of course) for sharing in the experience that is pursuing a Masters degree.

June and Phil McDougall, for lifting my spirits in times of frustration.

Smriti Sharma, Wesley Lombard and Alex Joiner for so willingly assisting during data collection (and providing much needed entertainment).

Andrew Elliott for graciously listening to my ramblings and providing me with an outlet for my ideas.

The individuals who so willingly and enthusiastically dedicated their time and energy to partake in this research.

The financial assistance from the Andrew Mellon Foundation Scholarship towards this research is hereby acknowledged. Opinions expressed and conclusions arrived at, are those of the author and are not necessarily to be attributed to Rhodes University or the donor.

TABLE OF CONTENTS

	PAGE
CHAPTER I	
INTRODUCTION	
BACKGROUND TO THE STUDY	1
STATEMENT OF THE PROBLEM	4
RESEARCH HYPOTHESES	4
STATISTICAL HYPOTHESES	5
DELIMITATIONS	6
LIMITATIONS	7
 CHAPTER II	
REVIEW OF RELATED LITERATURE	
INTRODUCTION	9
MANUAL MATERIALS HANDLING	10
SYSTEMS APPROACH	11
PUSHING AND PULLING	13
THE CONTEMPORARY JOB PROFILE	13
FUNDAMENTAL CONCEPTS OF PUSHING AND PULLING	14
STATIC AND DYNAMIC EXERTIONS	15
BIOMECHANICS OF PUSHING	16
HAND FORCE EXERTION	16
EPIDEMIOLOGY	18
USABILITY OF MANUAL VEHICLES	20
Design Factors	21
Task Factors	27
Environmental Factors	30
Operator Factors	31
PERCEPTUAL ASPECTS OF PUSHING AND PULLING	33
BODY DISCOMFORT SCALE	33
TO PUSH OR PULL?	34

SPINAL KINEMATICS	35
INTRODUCTION	35
BIOMECHANICAL LOGIC	37
ASSESSMENT OF SPINAL LOADING	40
Static Assessment	40
Dynamic Assessment	43
Trunk Motion	43
Low Back Disorder Risk Model	44
MUSCLE ACTIVITY	45
CONCLUSION	48
 CHAPTER III	
METHODOLOGY	
INTRODUCTION	49
PILOT STUDIES	49
SELECTION OF WALKWAY	50
SELECTION OF LOAD MASS	50
SELECTION OF MANUAL VEHICLE	51
SPEED OF PUSHING AND PULLING	51
MUSCLE SELECTION	52
EXPERIMENTAL DESIGN	54
INSTRUMENTATION	55
ANTHROPOMETRIC AND DEMOGRAPHIC VARIABLES	55
Stature: Harpenden Stadiometer	56
Body Mass: Toledo Scale	56
Acromiale and Radiale Heights: Anthropometer	57
BIOMECHANICAL AND PERCEPTUAL VARIABLES	57
Hand forces: Chatillon® DFS Digital Force Gauge	57
Spinal kinematics: Industrial Lumbar Motion Monitor™	58
Muscle activity: Megawin ME6000 Muscle Tester	61
Digital Camera	63

Perceptual discomfort: Body Discomfort Scale	63
SUBJECT CHARACTERISTICS	64
ETHICAL CONSIDERATIONS	64
EXPERIMENTAL PROCEDURES	65
STATISTICAL TREATMENTS	68
 CHAPTER IV	
RESULTS	
HAND FORCE EXERTION	69
INITIAL FORCES	70
SUSTAINED FORCES	72
ENDING FORCES	74
COMPARISON OF INITIAL, SUSTAINED AND ENDING FORCES	76
SPINAL KINEMATICS	78
SPINAL DISPLACEMENTS	78
Mean Sagittal Position	78
Maximum Sagittal Range of Motion	80
Mean Lateral Position	82
Maximum Lateral Range of Motion	84
Mean Twisting Position	86
Maximum Twisting Range of Motion	87
SPINAL VELOCITIES	89
Maximum Sagittal Velocity	89
Maximum Lateral Velocity	91
Maximum Twisting Velocity	93
SPINAL ACCELERATIONS	94
Maximum Sagittal Acceleration	94
Maximum Lateral Acceleration	96
Maximum Twisting Acceleration	97
MUSCLE ACTIVITY	98
ARM MUSCLES	98

SHOULDER MUSCLES	100
BACK MUSCLES	103
BODY DISCOMFORT	106
CONCLUSION	108
 CHAPTER V	
DISCUSSION	
INTRODUCTION	109
HAND FORCE EXERTION	109
HAND FORCE EXERTION RELATIVE TO BODY MASS	111
COMPARISON WITH EXISTING ACCEPTABLE LIMITS	112
SPINAL KINEMATICS	117
LOWER BACK DISORDER RISK OF PUSHING AND PULLING	117
LOW BACK DISORDER RISK MODEL	120
JOINT LOADING AT L ₅ /S ₁	121
MUSCLE ACTIVITY	124
MUSCLE PROFILE	124
MUSCLE FATIGUE	127
COMPARISON OF PHYSICAL AND PERCEIVED STRAIN	128
INTEGRATED DISCUSSION	130
 CHAPTER VI	
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS	
INTRODUCTION	133
SUMMARY OF PROCEDURES	133
SUMMARY OF RESULTS	136
HAND FORCE EXERTION	136
SPINAL KINEMATICS	138
MUSCLE ACTIVITY	140
BODY DISCOMFORT	142
RESPONSE TO HYPOTHESES	143

CONCLUSIONS	144
HAND FORCE EXERTION	144
SPINAL KINEMATICS	145
MUSCLE ACTIVITY	146
BODY DISCOMFORT	147
RECOMMENDATIONS	148
 REFERENCES	 151
BIBLIOGRAPHY	166
APPENDICES	168
APPENDIX A: HABITUATION AND EXPERIMENTATION	168
APPENDIX B: DATA COLLECTION	174
APPENDIX C: SUMMARY REPORTS	184

LIST OF TABLES

TABLE		PAGE
I	Approaches to task design	12
II	Recommendations of handle height	22
III	Preference for push/pull based on hand force exertion	35
IV	Static and dynamic assessments of spinal loading	42
V	Muscle selection for final experimentation	53
VI	Design matrix of experimental conditions	54
VII	Descriptive characteristics of participants (n=36)	64
VIII	Impact of technique on mean peak initial hand forces (N) for each load	71
IX	Impact of technique on mean sustained hand forces (N) for each load	73
X	Impact of technique on mean peak ending hand forces (N) for each load	75
XI	Impact of technique on mean sagittal position	79
XII	Impact of technique on mean maximum sagittal range of motion	81
XIII	Impact of technique on mean lateral position	83

XIV	Impact of technique on mean maximum lateral range of motion	85
XV	Impact of technique on mean twisting position	86
XVI	Impact of technique on mean maximum twisting range of motion	88
XVII	Impact of technique on mean maximum sagittal velocity	90
XVIII	Impact of technique on mean maximum lateral velocity	92
XIX	Impact of technique on mean maximum twist velocity	94
XX	Impact of technique on mean maximum sagittal acceleration	95
XXI	Impact of technique on mean maximum lateral acceleration	96
XXII	Impact of technique on mean maximum twist acceleration	97
XXIII	Muscle activity of brachioradialis and triceps brachii (% of MVC)	99
XXIV	Muscle activity of deltoid muscles (% of MVC)	102
XXV	Muscle activity of back muscles (% of MVC)	104
XXVI	Perceptual ratings of body discomfort, indicating frequency of ratings and mean intensity of discomfort, in brackets	107
XXVII	Requisite forces as a percent of body mass, in Newtons	112

XXVIII	Spinal kinematics in relation to recommendations by Marras et al. (1995)	119
XXIX	Compressive and shear forces acting on L ₅ /S ₁ as a result of postures adopted when initiating movement	122
XXX	Muscle profile for each push/pull technique, based on activation levels	125
XXXI	Comparison of perceived areas of discomfort with muscle activity	129
XXXII	Statistically significant differences ($p < 0.05$) of measures between conditions	131

LIST OF FIGURES

FIGURE		PAGE
1	Pushing as evidenced in the South African automotive industry	1
2	Force output during pushing (adapted from van der Beek et al. , 1999) and pulling (adapted from Bennett et al. , 2008) of a four-wheeled manual vehicle	17
3	Factors influencing usability of manual vehicles (adapted from Mack et al. , 1995 and Jung et al. , 2005)	21
4	Forces acting on the spine (adapted from Marras, 2000)	38
5	Loading components on the spine (Marras, 2000)	38
6	Load-tolerance relationship (adapted from McGill, 1997 and Marras, 2000)	39
7	Three dynamic push/pull techniques under investigation	55
8	Handle of pallet jack and Chatillon adaptor handle	58
9	Placement of lumbar motion monitor on participant's back	60
10	Electrode placement for the eight muscles under investigation	62
11	Typical tracings of force output for pushing and pulling, with motion phases indicated	70

12	Impact of load on mean peak initial hand forces for all techniques	72
13	Impact of load on mean sustained hand forces for all techniques	74
14	Impact of load on mean peak ending hand forces for all conditions	76
15	Differences in force output between motion phases for all conditions	77
16	Impact of load on mean sagittal position	80
17	Impact of load on mean maximum sagittal range	82
18	Cyclic nature of lateral displacement due to walking (at 500kg)	83
19	Impact of load on mean maximum lateral range	86
20	Cyclic nature of spinal twisting due to walking (at 500kg)	88
21	Impact of load on maximum twisting angle	89
22	Impact of technique on mean maximum sagittal velocity	90
23	Impact of load on mean maximum sagittal velocity	91
24	Impact of load on maximum lateral velocity	93
25	Impact of load on mean maximum sagittal acceleration	95
26	Muscle activity of brachioradialis and triceps brachii	100
27	Muscle activity of deltoid muscles	103

28	Muscle activity of back muscles	106
29	Inter-study differences in linear load-force relationship (Resnick and Chaffin, 1995; Donders et al. , 1997; van der Beek et al. , 2000; Bennett et al. , 2008)	110
30	Comparison of initial forces to existing guidelines for acceptable limits	114
31	Comparison of sustained forces to existing guidelines for acceptable Limits	115
32	Comparison of ending forces to existing guidelines for acceptable limits	116
33	Probability of high risk group membership for lower back disorders	121

CHAPTER I

INTRODUCTION

BACKGROUND TO THE STUDY

Lifting, lowering and carrying have traditionally been the primary means by which loads were displaced in the vocational setting. During lifting in particular, the lumbosacral joint, L₅/S₁, advocated as the weakest link in the vertebral column, is however placed under considerable stress, rendering the worker susceptible to injury. Furthermore, as lifting is frequently cited in relation to lower back pain (LBP) (Bigos *et al.*, 1986; Resnick and Chaffin, 1995; de Looze *et al.*, 2000; Jansen *et al.*, 2002), it is intuitive to recommend avoiding this type of activity. This has initiated changes in job design through the implementation of manual transport aids and vehicles such as mechanical hoists, articulated arms, trolleys and carts (Resnick and Chaffin, 1995; Nussbaum *et al.*, 2000). Although this has reduced the occurrence of lifting, repetitive pushing and pulling activities have become increasingly common.



Figure 1. Pushing as evidenced in the South African automotive industry

The nature of horizontal pushing/pulling means that the support provided by the ground (Mital *et al.*, 1993) and the minimisation of vertical gravitational forces (Okunribido and Haslegrave, 2008) lessen the workload and prevalence of injuries compared to lifting. This is however a common and sometimes erroneous assumption (Mital *et al.*, 1993), specifically when manual vehicles and devices are poorly

designed (Mathisson **et al.**, 1994; Mack **et al.**, 1995; Sillanpaa **et al.**, 1999). This has been demonstrated in the continued high incidence, severity and costs of musculoskeletal disorders (MSDs) (Mital and Ramakrishan, 1999). It is thus conceivable that changes in job characteristics simply alter the stresses placed on the worker (Resnick and Chaffin, 1997) and do not inherently reduce the risk of injury (Nilsson and Dahlman, 1994; Resnick and Chaffin, 1995).

In light of the fact that pushing/pulling are prevalent in a myriad of occupational settings, including healthcare services (Das **et al.**, 2002), warehousing, agriculture (Kumar, 1995a; Imrhan, 2003), retail (Kumar **et al.**, 1995), refuse collection (Kuijer **et al.**, 2007) and often make up sub-components of other tasks (Hoozemans **et al.**, 2002), it is no surprise that they comprise approximately half of all manual materials handling (MMH) in industry (Baril-Gingras and Lortie, 1995; van der Beek **et al.**, 1999). This suggests that a significant proportion of injuries to the musculoskeletal system may in part be related to push/pull activities and that one of the most sizeable issues facing industry, LBP, may not be solely or principally attributable to lifting, although it has traditionally been the topic of discussion centred on epidemiological research (Lavender **et al.**, 1998). Pushing/pulling have further been implicated in the proliferation of MSDs to others areas of the upper body, specifically the shoulder/neck region and upper extremities (Hoozemans **et al.**, 1998; Hoozemans **et al.**, 2002). Some authors have gone so far as to argue that the shoulders are more likely to become impaired than the lower back (Hoozemans **et al.**, 2002; van Nieuwenhuysen **et al.**, 2004).

Although general literature surrounding pushing/pulling is limited, existing studies have principally been concerned with static tasks despite the knowledge that most manual activities are dynamic in nature (Todd, 2005). Cognisance must be taken of this fact considering that dynamic work is associated with a higher risk of injury compared to static work (Allread **et al.**, 2000). This has relevant implications for the cause of lower back injuries, with scientific evidence indicating that trunk motion, resulting from dynamic movement, is essential in predicting the degree of risk more

accurately (Marras **et al.**, 1993; Marras **et al.**, 1995). In relation to LBP, most research has focused on investigating hand forces produced, as they are alleged to be indices of spinal loading (Resnick and Chaffin, 1995). Yet the role that lumbar segment motion plays in the onset of these injuries during pushing and pulling is also of interest. Within industry, dynamic pushing and pulling may be performed unilaterally (one-handed) or bilaterally (two handed) and may involve forward or backward walking. Most often, two-handed forward pushing, two-handed backward pulling and one-handed forward pulling occur. This suggests that dynamic movement of the trunk may change between push/pull techniques, imposing different demands on the musculoskeletal system. It is thus evident that such activities should be investigated as possible contributors to MSDs.

Whereas the lower back experiences the most strain during lifting, the upper extremities and shoulder region (Hoozemans **et al.**, 1998; Hoozemans **et al.**, 2002) may incur greater stress during pushing/pulling. This has not however been well quantified. Since muscular strain has been shown to be a critical element of preventing musculoskeletal injuries (Grant and Habes, 1997), documenting electric activity of the working muscles is a necessary part of identifying the optimal push/pull technique. It is in this context that this study aimed to gauge myoelectric activity of the upper body muscles to determine where the majority of muscular effort was derived. Coupled with this, subjective perceptual ratings of discomfort were used to identify the body areas enduring the greatest stress and comparatively to determine if individuals experience discomfort in the same areas that exert the most muscular effort.

To determine which mode of pushing/pulling least taxes the human operator, the current study undertook to investigate hand force production, spinal kinematic variables, upper body muscle activity and body discomfort of the three most typically adopted techniques, namely two-handed forward pushing, two-handed backward pulling and one-handed forward pulling, using an industrial pallet jack. Although one-handed pushing may occur, it is very rarely practiced in industry and was therefore not considered instrumental in the proliferation of workplace disorders. The variables

were measured under two different load masses, as load is known to influence hand forces (Resnick and Chaffin, 1995; Donders **et al.**, 1997; Jung **et al.**, 2005; Todd, 2005; Cripwell, 2007; Bennett **et al.**, 2008), and therefore spinal load (Resnick and Chaffin, 1995). In addition, the impact of the independent variables on hand forces was gauged with consideration of the initial, sustained and ending motion phases of dynamic pushing/pulling to gain a more comprehensive understanding of the inherent risk of injury.

STATEMENT OF THE PROBLEM

Determining whether two-handed forward pushing, two-handed backward pulling and one-handed forward pulling places the least strain on the lower back and upper body during dynamic work is paramount in the design of safe guidelines for MMH tasks. Achieving the aims of the research required the quantification of the key determinants of strain, namely hand force exertion, trunk motion characteristics and muscle activity, which few studies have documented. Moreover, numerous investigations have reported that strain manifests in other body regions, emphasising the need for self-reports in the form of body discomfort ratings. The objectives of the current research were hence to quantify the workload of various techniques of pushing/pulling of two load masses, using biomechanical and perceptual measures. This, in turn, allowed for the identification of a preferable dynamic push/pull technique.

RESEARCH HYPOTHESES

Two-handed forward pushing and two-handed backward pulling were expected to elicit lower hand forces, trunk motion characteristics (position, velocity and acceleration in all cardinal planes), muscle activity and perceptual responses (body discomfort) than one-handed forward pulling at the same loads. It was postulated that responses would be different for two-handed pushing and two-handed pulling at the same loads and that all responses would be higher using a 500kg load compared to a 250kg load for the same technique. Finally, it was expected that hand forces exerted in the initial phase would exceed those of either the sustained or ending phases, and that ending forces would be higher than sustained forces.

STATISTICAL HYPOTHESES

Impact of technique

Hypothesis 1a: No significant differences exist between biomechanical responses for each technique at the same load.

$$H_0: \mu_{\text{BIO Push 1,2}} = \mu_{\text{BIO 2-h pull 1,2}} = \mu_{\text{BIO 1-h pull 1,2}}$$

$$H_a: \mu_{\text{BIO Push 1,2}} \neq \mu_{\text{BIO 2-h pull 1,2}} \neq \mu_{\text{BIO 1-h pull 1,2}}$$

Where BIO refers to: Hand Forces, Spinal Kinematics, Muscle Activity

Push =two-handed forward pushing

2-h pull =two-handed backward pulling

1-h pull =one-handed forward pulling

1= 250kg 2=500kg

Hypothesis 1b: No significant differences exist between perceptual responses (body discomfort) for each technique at the same load.

$$H_0: \mu_{\text{BD Push 1,2}} = \mu_{\text{BD 2-h pull 1,2}} = \mu_{\text{BD 1-h pull 1,2}}$$

$$H_a: \mu_{\text{BD Push 1,2}} \neq \mu_{\text{BD 2-h pull 1,2}} \neq \mu_{\text{BD 1-h pull 1,2}}$$

Where BD refers to: Body Discomfort responses

Push =two-handed forward pushing

2-h pull =two-handed backward pulling

1-h pull =one-handed forward pulling

1= 250kg 2=500kg

Impact of load

Hypothesis 2a: No significant differences exist between biomechanical responses for loads using the same technique.

$$H_0: \mu_{\text{BIO 250kg (Push, 2-h pull, 1-h pull)}} = \mu_{\text{BIO 500kg (Push, 2-h pull, 1-h pull)}}$$

$$H_a: \mu_{\text{BIO 250kg (Push, 2-h pull, 1-h pull)}} \neq \mu_{\text{BIO 500kg (Push, 2-h pull, 1-h pull)}}$$

Where BIO refers to: Hand Forces, Spinal Kinematics, Muscle Activity

Push =two-handed forward pushing

2-h pull =two-handed backward pulling

1-h pull =one-handed forward pulling

Hypothesis 2b: No significant differences exist between perceptual responses (body discomfort) for loads using the same technique.

$$H_0: \mu_{BD \text{ 250kg (Push, 2-h pull, 1-h pull)}} = \mu_{BD \text{ 500kg (Push, 1-h pull, 2-h pull)}}$$

$$H_a: \mu_{BD \text{ 250kg (Push, 2-h pull, 1-h pull)}} \neq \mu_{BD \text{ 500kg (Push, 2-h pull, 1-h pull)}}$$

Where BD refers to: Body Discomfort responses

Push =two-handed forward pushing

2-h pull =two-handed backward pulling

1-h pull =one-handed forward pulling

Hypothesis 3: No significant differences exist between the forces exerted during the initial, sustained and ending motion phases for the same condition.

$$H_0: \mu_{F1 \text{ Ini}} = \mu_{F1 \text{ Sus}} = \mu_{F1 \text{ End}}$$

$$H_a: \mu_{F1 \text{ Ini}} \neq \mu_{F1 \text{ Sus}} \neq \mu_{F1 \text{ End}}$$

Where F1 refers to: Hand Forces for condition 1(note this hypothesis applies to each condition)

Ini=Initial phase; Sus=Sustained phase; End=Ending phase

DELIMITATIONS

The present study aimed at investigating which pushing/pulling technique imposed the least stress on the human operator through the investigation of biomechanical and perceptual measures. To augment the reliability of responses, certain impinging criteria were controlled. A large sample of 36 males, drawn from a student population at Rhodes University, made up the sample group. Prior to experimentation, self reports indicated that participants were free of illness and MSDs, specifically relating to the back and upper extremities. The ages of participants ranged from 19 to 28 years, stature was delimited to between 1700mm and 1900mm and all volunteers were right-hand dominant. Controlling these variables meant that inter-subject variability was minimised and findings could be applied to populations groups with similar characteristics.

Experimentation occurred under controlled laboratory conditions throughout the day, negating the effect of ambient factors such as temperature, light and noise. In this environment, it was possible to standardise methodological factors. Under all

conditions, the same standard industrial pallet jack was used. It had a fixed handle height and for this reason, radiale and acromiale heights of the volunteers were measured, ensuring that the handle location fell between these anthropometric landmarks. Since handle height affects body posture (Ayoub and McDaniel, 1974) and force output (Daams, 1993), it was necessary to standardise this variable. The subjects were required to push and pull the pallet jack on a wooden walkway measuring 10m in length. This surface was adequate to maintain a low rolling coefficient of friction between the wheels of the pallet jack and floor, limiting the stresses experienced by individuals. Subjects were also required to wear rubber soled training shoes to allow a high shoe/floor coefficient of friction to prevent slipping.

Testing procedures were also standardised. Lines at 1.5m on either side of the walkway were marked. On starting, participants were required to have attained the appropriate walking speed within the first marked line and on ending, they were required to begin slowing down at the 8.5m line. To initiate movement of the pallet jack, a standardised foot position was adopted with the right foot placed behind the left in a staggered posture. Walking speed was controlled to between 0.45 and 0.55 statures.s^{-1} , making certain that all subjects were physically taxed to an equal extent and permitting accurate comparison of measured responses between conditions. If speed was not within the specified range, another trial was performed. To ensure intra-subject consistency, three successful trials were warranted. This was determined through consistency of walking speed and of force output per condition. All experimental conditions were completed in one testing session, allowing electrode placement to be standardised for each subject and for all conditions.

LIMITATIONS

Despite efforts to rigorously minimise confounding variables from affecting the reliability of measures, some factors were uncontrollable. Although experimentation occurred in a controlled laboratory environment, allowing for the exclusion of certain other influencing environmental variables, laboratory conditions do not always accurately reflect work settings, which may compromise a study's external validity.

Participants were student volunteers, implying that although they may have some anthropometric and demographic characteristics in common with some industrial workers, they do not wholly represent all workers performing manual tasks. Furthermore, diets and exercise habits were uncontrolled although verbal and written instructions were given to participants to maintain 'normal' eating and not to partake in strenuous exercise 24 hours prior to testing, which may have influenced results.

Another limitation was the familiarity of participants with equipment. Individuals were instructed verbally and in writing how to use the body discomfort rating scale, yet there is no way of knowing whether all completely understood its use, or whether the ratings provided were accurate reflections of the discomfort perceived. Similarly, subjects were unfamiliar with wearing the Industrial Lumbar Motion Monitor (iLMM) and surface electrodes, which may have had an impact on performance. These pieces of equipment are however considered to be non-invasive and interfere minimally with the task being completed.

Although every care was taken to minimise cross-talk from nearby muscles not under investigation by ensuring correct electrode placement over the muscle belly and carefully selecting muscles situated close to the surface of the skin, interference may have occurred. Finally, electrode placement on small muscles is sometimes difficult, but the use of male subjects, whose muscles are generally larger and more easily palpated than those of females, facilitated easy access to the muscle groups of interest.

CHAPTER II

REVIEW OF RELATED LITERATURE

INTRODUCTION

The last few decades have witnessed an escalation in repetitive pushing and pulling in the industrial sector, with attempts being made to minimise lifting, lowering and carrying (de Looze **et al.**, 2000; Granata and Bennett, 2005; Li **et al.**, 2008), known to be related to musculoskeletal injuries (Bigos **et al.**, 1986; Resnick and Chaffin, 1995). However literature regarding pushing and pulling is still in its infancy, with few definitive guidelines pertaining to the overall usability of manual handling vehicles and devices. There has generally been a lack of standardisation in methodologies, differences in variables of interest and disregard for the context in which work is performed, resulting in many sundry and sometimes vague recommendations. These activities have become synonymous with work-related musculoskeletal disorders (WMSDs) however, suggesting that recommendations need to be more stringently applied and must be relevant for the intended context.

While literature dealing with the fundamental principles of pushing and pulling are extensive, there are discrepancies. For example, the majority of research has been on static as opposed to dynamic exertions. Where dynamic pushing and pulling have been studied, little cognisance has been afforded to the impact of different techniques and where comparisons have occurred, the objective has largely been to discover whether pushing or pulling is less strenuous on the worker, often through the investigation of hand forces exerted. Related research often focuses only on one criterion to define safe working limits whereas a holistic integration of criteria may be more appropriate in making meaningful recommendations. The aim of this study was therefore to gauge the hand forces, spinal kinematic variables, muscle activity of the upper body and body discomfort to determine which dynamic push/pull technique evokes the least strain in individuals. This will allow workers to make informed decisions about how to meet the requirements of the job without compromising safety, and without the need for expensive and extensive changes to the manufacturing process.

MANUAL MATERIALS HANDLING

Manual materials handling (MMH) continues to form an integral part of industrial processes, despite rapid advances in technology, robotics (Hoozemans **et al.**, 1998; Nussbaum and Chaffin, 1999; Davis and Marras, 2000; Nussbaum **et al.**, 2000) and the implementation of occupational interventions (Bos **et al.**, 2006). Typically it involves the use of large muscle groups to manipulate loads with the hands while performing static or dynamic work and encompasses lifting, lowering, carrying, pushing and pulling (Louhevaara, 2003). A prime reason for the continuance of manual labour to drive work processes is related to man's ability to adapt to a broad array of tasks that must be completed in occupational settings. Secondly, organisations may lack the capital to invest in machinery or the space to install automated equipment (Mital, 1999). Even where technological advances have occurred, there has been no subsequent reduction in the reliance on human power and, as argued by Marras **et al.** (1995) MMH will continue to be a necessary part of many occupations. Regardless of the rationale, these tasks evoke strain in the human operator (Mack **et al.**, 1995; Li **et al.**, 2008), specifically when the workload exceeds the capacity of the worker (Dempsey, 1998). Injuries to the musculoskeletal system are a concern, causing pain and suffering to the worker and placing organisations under economic pressure. This negative scenario has nationwide implications, with direct and indirect costs of work-related musculoskeletal disorders and injuries amounting to billions of dollars annually (Webster and Snook, 1994).

Although the exact figures are unknown (Piedrahita, 2006), costs are related to such factors as compensation, health-care and work-time lost (Maetzi and Li, 2002). An analysis based in the United States revealed that MMH accounted for over 36% of the claims submitted to a workmans' compensation insurer and 35% of all claims costs, with the total expenditure exceeding U.S.\$750 000 000 annually (Dempsey and Hashemi, 1999). Irrespective of attempts to minimise the dangers associated with these types of tasks, Mital and Ramakrishan (1999) reported that over the decade 1984 to 1994, the prevalence of injuries had escalated, leading to the conclusion that the severity and monetary cost of injuries may also have intensified. As such, the ergonomist is faced with the two-fold

objective of ensuring worker safety and well-being while concurrently aiming at improving quality and quantity of productivity: a complex situation.

Systems Approach

As early as the 18th Century, Smith (1776) recognised that workers are likely to experience ill-health and cause themselves injury when they work excessively, and stated:

“...the man who works so moderately, as to be able to work constantly, not only preserves his health longest, but, in the course of the year, executes the greatest quantity of work” (Smith, 1776; see Dempsey and Mathiassen, 2006, pp 34).

Despite this realisation over two centuries ago, the present-day human operator is likely to endure arduous stresses similar to those experienced by his predecessor because the capacity of the human body is often surpassed (Mital, 1999). This is a direct result of the physically demanding nature of MMH activities which predispose the worker to stress, resulting in strain on the cardiopulmonary and musculoskeletal systems (Dempsey, 1998). To guard against ill-health caused by excessive work, the demands of the task must be maintained within acceptable tolerance limits so as to not outweigh the physical capacity of the human operator (Ayoub **et al.**, 1983). Developing on this idea of “fitting the task to the man,” Ayoub **et al.** (1983) reported that the ratio between the task demands and physical capacity of the worker determines if a task is likely to cause impairment. The ratio has a direct impact at an individual and industrial level, such that if the worker is unable to effectively manage the task demands, discomfort, fatigue and injury will ensue, compromising quality and quantity of productivity. If the demands are maintained within acceptable parameters, the outcome will, in contrast, be quality performance and enhanced productivity. Due to the inter-relatedness between effects at both levels, it is paramount to consider them in unison. To focus solely on one will not necessarily optimise system performance (Dempsey, 1998).

Dempsey (1998) coined this approach of determining risk the “*Systems Approach*,” according to which the task demands are quantified in terms of organisational, material, task/workplace and environmental factors while personal

characteristics, physiological, biomechanical and psychophysical capacities must be borne in mind when determining the worker capacity.

Using the principle concepts of biomechanics, physiology, psychophysics and epidemiological evidence, various criteria have been established to define ceiling limits for the ratio (Leamon, 1994; Shoaf **et al.**, 1997; Dempsey, 1998; Dempsey, 1999; Dempsey and Mathiassen, 2006). A value is calculated based on the criteria and is then compared to some existing standard to determine the acceptability of the task. A summary of the approaches, including the fundamental aims, criteria and limitations are shown in Table I.

Table I. Approaches to task design

	<i>Biomechanics</i>	<i>Physiology</i>	<i>Psychophysics</i>	<i>Epidemiology</i>
Objective	Prevent excessive strain on musculoskeletal system	Prevent fatigue (whole-body fatigue and to a lesser extent local fatigue)	Design tasks to be acceptable to majority of workers Determine what worker is willing to do, not what worker can do	Forecast incidence, severity of injury by identifying injury patterns Compare and validate criteria
Criteria	Compression limits for L ₄ /L ₅ or L ₅ /S ₁ or maximal joint torques	Metabolic cost (derived from oxygen consumption)	Modify weight, frequency, force to maximum acceptable values sustainable for eight hour workday	Pathology of injury
Application	Low frequency tasks	High frequency tasks	Moderate frequency tasks	Prevention of injuries
Limitations	Spinal compression derived from cadaver data (not necessarily reflective of <i>in vivo</i> spine) Focus primarily on compression, not shear or torsion forces	Difficulty specifying acceptable ceiling limit for oxygen consumption relative to maximal oxygen consumption Difficulty selecting test for aerobic capacity	Subjective nature of psychophysical studies Trials of short duration to predict acceptability of work for eight hours	Difficulty deriving valid criteria from epidemiological results Fail to establish workloads at which task becomes hazardous Univariate analyses (but injuries multifactorial in nature)

Fundamentally, the concepts are conflicting in nature, implying that tolerance limits may vary according to the criteria adopted (Dempsey, 1998; Ayoub and Dempsey, 1999). For example, by decreasing load mass, the biomechanical system of the operator is protected, but this is accompanied by a subsequent decline in

productivity. To maintain the same work output, the frequency of the task must be increased, placing the worker under physiological stress (Jung and Freivalds, 1991). In essence, the biomechanical approach opts for lower loads for frequent exertions while the physiological approach opts for higher loads for infrequent exertions (Ayoub, 1992). Jung and Freivalds (1991) opined that implementation of a single approach does not indicate the combined effect of the physical demands of a task, resulting in contradictory recommendations. To find a solution, Ayoub (1992) and Dempsey (1998) suggested that the most conservative value be applied.

PUSHING AND PULLING

The Contemporary Job Profile

The job profile of industrial tasks has changed considerably in recent times, with pushing and pulling often replacing lifting and carrying (de Looze **et al.**, 2000; Granata and Bennett, 2005; Li **et al.**, 2008), through the introduction of manual vehicles and aids (Chaffin **et al.**, 1999). The primary facilitator steering this change relates to lifting and its known association with the proliferation of lower back disorders (Bigos **et al.**, 1986; Resnick and Chaffin, 1995). The use of these devices facilitates movement of heavier loads (van der Beek **et al.**, 1999; Lett and McGill, 2006) without the worker having to support the entire burden of the load and results in lower vertical gravitational forces (Okunribido and Haslegrave, 2008) seemingly lessening the workload and enhancing the work process, compared to lifting. The concomitant necessity to push/pull (Al-Eisawi **et al.**, 1999a) is however a concern because repetitive pushing/pulling may be aetiologically linked to the onset of MSDs, presenting a contradiction; the devices originally designed to alleviate injuries are in fact causing them. Marras (2000) elucidated that the shift in job profile means that load management as opposed to load support describes the nature of modern work, whereby controlling the inertial effects of the load make the job challenging.

Essentially pushing/pulling impose a different kind of stress on the worker, causing a new array of musculoskeletal injuries. The direction of the resultant hand forces is usually horizontal and the inertia of the devices contributes to the load being

transferred (Resnick and Chaffin, 1997), intensifying the stress on the lower back. These tasks may prompt unilateral exertions and loaded torso axial rotations (Resnick and Chaffin, 1997), neither of which have been investigated adequately. Moreover, 'smaller' muscle groups, such as those of the forearm, contribute greatly to the effort whereas lifting and carrying primarily make use of 'larger' muscles (James **et al.**, 2005). The problem is therefore that smaller muscles are placed under tremendous strain.

Although researchers have acknowledged the change in task demands, pushing/pulling activities are more challenging to assess compared to lifting since the direction of the force in the former (although usually horizontal) can differ at various stages of the activity (Laursen and Schibye, 2002). For this reason, Laursen and Schibye (2002) argued that shoulder torques are inclined to have varying magnitudes and directions. The complexity is further intensified when the lumbar back is considered because the torque produced by the push/pull force is counteracted by the torque produced by gravity, implying that even if force is amplified, spinal loading may be reduced (Schibye **et al.**, 2001).

Fundamental Concepts of Pushing and Pulling

Push/pull tasks are generally defined as the exertion of a force (primarily using the hand) on another person or object, given that the direction of the principal component of the resultant force is horizontal (Martin and Chaffin, 1972; Baril-Gingras and Lortie, 1995; Hoozemans **et al.**, 1998). The direction of force needs not however be completely horizontal (Glitsch **et al.**, 2007), provided that the deviation is small (Garg **et al.**, 1988; Imrhan, 2003). It is important to note that these definitions do not envelop the possibility of pushing primarily in the vertical direction, which is likely to occur during overhead work for example. As such, the use of amalgamated terms such as a lift-pull or lift-push, coined by Pheasant **et al.** (1982) to describe tasks in which the deviation from the horizontal is large, may be more apt.

Static and Dynamic Exertions

Although pushing and pulling are not often mutually exclusive, they are easily differentiated; in the former the effort is directed away from the body while in the latter it is directed towards the body (Hoozemans **et al.**, 1998; van der Beek **et al.**, 1999; Glitsch **et al.**, 2007). Both may involve static and dynamic exertions, or a combination of the two, with most dynamic efforts including a static component usually in the trunk and upper extremities (Garcin **et al.**, 1996; Hoozemans **et al.**, 1998). Static exertions, most often required to support objects and control certain apparatus (Imrhan, 2003), result in the object against which the force is exerted remaining stationary (Lee **et al.**, 1991). Conversely, dynamic exertions, usually employed to transport loads (Imrhan, 2003), cause the object to become displaced (Lee **et al.**, 1991).

Static tasks have historically been at the core of scientific investigations (Lee **et al.**, 1991; Resnick and Chaffin, 1995), regardless of the assertion that work performed in industry is usually dynamic in nature (Todd, 2005). This is important, given that the fundamental differences between the way in which static and dynamic activities are performed in terms of posture and force generation prescribe that each must be approached accordingly. For the same level of effort, body postures vary between the two, impacting on lower back loading, and implying that the ceiling parameters derived statically may not be applicable to dynamic exertions. This was acknowledged by Resnick and Chaffin (1995) who stated that postures change rapidly during dynamic pushing/pulling and as such, optimal postures are not practicable for the duration of the task. Under low accelerations peak pushing forces may approximate those of static efforts, suggesting that static estimations may be used to predict peak pushing forces at low accelerations, but when accelerations are high, dynamic measures are paramount (Resnick and Chaffin, 1995). Some authors have advocated that static standards are inappropriate for dynamic exertions when considering push/pull strength, with dynamic strengths being significantly lower than static ones (Kumar **et al.**, 1995; Mital **et al.**, 1995).

Arguably, dynamic exertions are more complex than static ones, both from a performance and assessment perspective. During dynamic push/pull actions, in addition to producing adequate force to induce motion, the user must be able to resume balance should the manual vehicle move unpredictably (Lee **et al.**, 1991). The challenge is further augmented because the object being displaced does not necessarily allow for the full support of the operator's body as is the case for static pushing and pulling. At such times the operator is forced to reduce stride length or assume awkward working postures to overcome the potential instability, often leading to overexertion injuries (Lee **et al.**, 1991).

Dynamic pushing/pulling may occur with the use of one or two hands and may involve forward or backward walking. The most commonly evidenced techniques are two-handed forward pushing, two-handed backward pulling and one-handed forward pulling, while the use of only one hand to control a manual vehicle as well as backward pushing is rarely performed. According to Li **et al.** (2008) the technique employed is a function of load, with light loads being moved with either one or two hands and heavy loads with two hands.

BIOMECHANICS OF PUSHING/PULLING

Hand Force Exertion

Due to the linear relationship between hand force exertion and biomechanical stress at the lower back (Jansen **et al.**, 2002), hand forces are considered indicative of the extent of risk of injury (Hoozemans **et al.**, 1998; van der Beek **et al.**, 1999). Most research related to pushing/pulling has subsequently been aimed at gauging hand forces and lumbar loading.

Forces produced during dynamic exertions are easily differentiated into three components (Figure 2, overleaf): these are the initial force to accelerate the object from its stationary position (Snook, 1978; Snook and Ciriello, 1991; Jansen **et al.**, 2002; Hoozemans **et al.**, 2007), the sustained force to maintain motion (Snook, 1978; Snook and Ciriello, 1991; Jansen **et al.**, 2002; Hoozemans **et al.**, 2007) and the ending or restraining force to decelerate the object and bring it to a standstill (Ferreira **et al.**, 2004).

Consideration of all three motion phases is crucial when determining the hazards associated with pushing/pulling because forces exerted during each motion phase may vary (Ferreira **et al.**, 2004) in magnitude, duration or both. This implies that the type of risk may depend on the motion phase. Many authors (Drury **et al.**, 1975; Mack **et al.**, 1995; van der Beek **et al.**, 2000; Laursen and Schibye, 2002; Hoozemans **et al.**, 2004; Jung **et al.**, 2005) have reported that forces exerted in the initial phase typically exceed those of other phases. However, under most circumstances, cognisance of the ending phase is mistakenly ignored. Yet sudden and unexpected movements during the ending phase sometimes result in excessive forces (Ferreira **et al.**, 2004), causing acute injuries. On the other hand, chronic injuries are more likely to be associated with the sustained phase, which is of the longest duration.

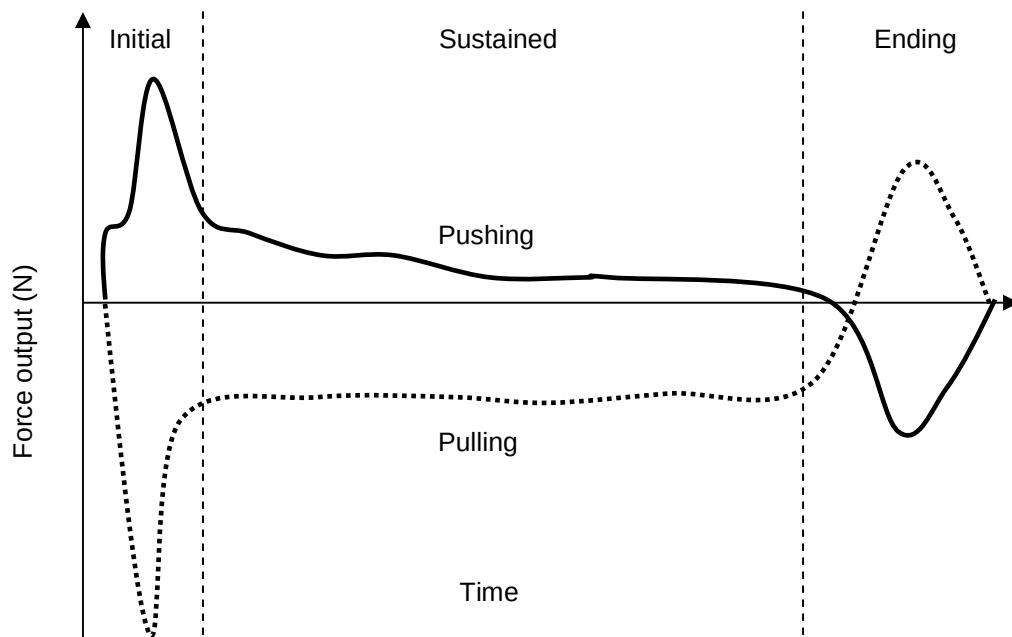


Figure 2. Force output during pushing (adapted from van der Beek **et al.**, 1999) and pulling (adapted from Bennett **et al.**, 2008) of a four-wheeled manual vehicle

While there are numerous recommendations to define ceiling limits for pushing/pulling, many neglect to mention contextual factors, such as distance of movement and frequency of exertions. Some are ambiguous and do not specify whether they apply to pushing or pulling or both. As such, there is no consensus

regarding upper limits for each motion phase, emphasising that cognisance of the context must be taken into account in the future.

Regarding initial forces, Eastman Kodak (1986) and Snook and Ciriello (1991), referring to the 90th percentile male recommend an upper limit of 225N while the HSE (1998) suggest a maximum of 245N for pushing/pulling between knuckle and waist height for males. For sustained forces, Snook and Ciriello (1991) advocate sustained forces of approximately 130N, while Eastman Kodak (1986) and the HSE (1998) are slightly more conservative at approximately 100N. 360N has been deemed satisfactory for emergency stopping by Eastman Kodak (1986) while 245N is recommended for ending forces (HSE, 1998). Since guidelines are highly variable, it is challenging to make changes to tasks in industry, suggesting research methodologies must be more closely aligned and be applicable to industrial activities.

Epidemiology

Arguably, pushing and pulling account for up to 50% of MMH tasks (Baril-Gingras and Lortie; 1995; van der Beek **et al.**, 1999) and must therefore contribute to a large proportion of workplace injuries. As such, some authors have argued that the overall workload and strain is not necessarily reduced through the use of manual transport aids and vehicles (Nilsson and Dahlman, 1994). Risks related to pushing and pulling result from two factors, namely overexertion of the human body and slip, trip and fall accidents (Chaffin **et al.**, 1983 Chaffin, 1987; Glitsch **et al.**, 2007), both of which are closely connected (Boocock **et al.**, 2006). Studies concerned with the workload of flight attendants reported that manoeuvring meal carts and trolleys is perceived to be highly physically demanding (Jäger **et al.**, 2007; Schaub **et al.**, 2007), with approximately 20% perceiving it to be the most stressful activity in flight (Winkel, 1983). Manning **et al.** (1984) reported that 13% of slipping accidents resulting in lower back pain can be attributed to push/pull activities.

Although aetiological evidence concluding that pushing and pulling are related to the development of MSDs is limited (Hoozemans **et al.**, 1998; Kuiper **et al.**, 1999), numerous authors have contended that a relationship does exist (Snook, 1978;

Frymoyer **et al.**, 1980; Pope, 1989). This is particularly true when ergonomic principles are neglected in tool design (Mathisson **et al.**, 1994; Mack **et al.**, 1995; Silanpaa **et al.**, 1999) or when tools are used inappropriately (Jung **et al.**, 2005).

Complaints involving the lower back are most common (Hoozemans **et al.**, 1998), with an estimated 9% to 20% of these injuries being accredited to pushing/pulling (Hoozemans **et al.**, 1998; Schibye **et al.**, 2001). Albeit, Hoozemans **et al.** (1998) argued that there is no definitive evidence to suggest a causal relationship because most investigations have been cross-sectional, whereas longitudinal studies are necessary. The shoulder/neck region and upper extremities, including forearms are also mentioned as potential areas of risk (Hoozemans **et al.**, 1998; Hoozemans **et al.**, 2002). It has in fact been argued that the risk is more closely related to the shoulders and not the lower back (Hoozemans **et al.**, 2002; van Nieuwenhuysse **et al.**, 2004). Although this assertion has not been rigorously researched (Hoozemans **et al.**, 1998) and guidelines specific to this are lacking (Kuijer **et al.**, 2007), it has been suggested that shoulder complaints are frequently associated with subtasks characteristic of pushing and pulling such as twisting and static loading of the shoulder musculature (Bjelle **et al.**, 1981, Tola **et al.**, 1988). Together, 70% of claims and claims costs can be attributed to the lower back and upper extremities (Dempsey and Hashemi, 1999).

With the escalated use of manual handling devices and vehicles, it has been predicted that the incidence of pushing/pulling will increase, together with concomitant injuries (Granata and Bennett, 2005; Todd, 2005). The severity of the situation dictates the need for guidelines regarding pushing and pulling, with the specific objectives of protecting the lumbosacral and shoulder regions. As Ferreira **et al.** (2004) indicate, epidemiological literature is severely lacking and outdated, with some being over ten years old. This condition, coupled with the continued introduction of manual vehicles and transport aids to the work setting, underscores the urgent need to update the epidemiological database (Ferreira **et al.**, 2004).

Usability of Manual Vehicles

According to Mack **et al.** (1995) often the most appealing response to the presence of risk of injury is the introduction of manual vehicles and handling devices. If well-designed they may be particularly effective in lessening the strain by minimising the overall task demands, decreasing the possibility of injury (Mack **et al.**, 1995) and allowing heavy loads to be transported with forces considered to be acceptable to the majority of the workforce (Ciriello, 2004). In fact, Straker **et al.** (1996) reported that not only were pushing/pulling rated as being less taxing than lifting, but the physical limits were twice that of lifting, lowering and carrying.

In reality, ergonomic rules are often partially or wholly omitted, with many operators experiencing difficulty using their manual vehicles (Mack **et al.**, 1995). Some require the exertion of significant forces (Okunribido and Haslegrave, 2008), implying that injuries are likely if the physical capacity of the worker is surpassed. Consequently, the speed at which work is completed and the efficiency of the work process are compromised, with the aids often being completely discarded, rendering them redundant (Mack **et al.**, 1995). In other cases, workers opt to use their hands because of the supplementary effort required to stow away the manual devices after use (Mathisson **et al.**, 1994). On the other hand, well-designed devices are often discarded because workers have not been adequately educated as to their effectiveness when used correctly (Chaffin **et al.**, 1999).

Although two- and four-wheeled vehicles are commonly implemented in industry, their designs are somewhat different, affecting their usability. The nature of two-wheeled vehicles means that in addition to the horizontal force needed to propel it forward, a vertical force is also necessary to support the load (Mack **et al.**, 1995). For the purposes of this investigation, the primary focus was on four-wheeled vehicles because they are employed more extensively in industry (Mack **et al.**, 1995).

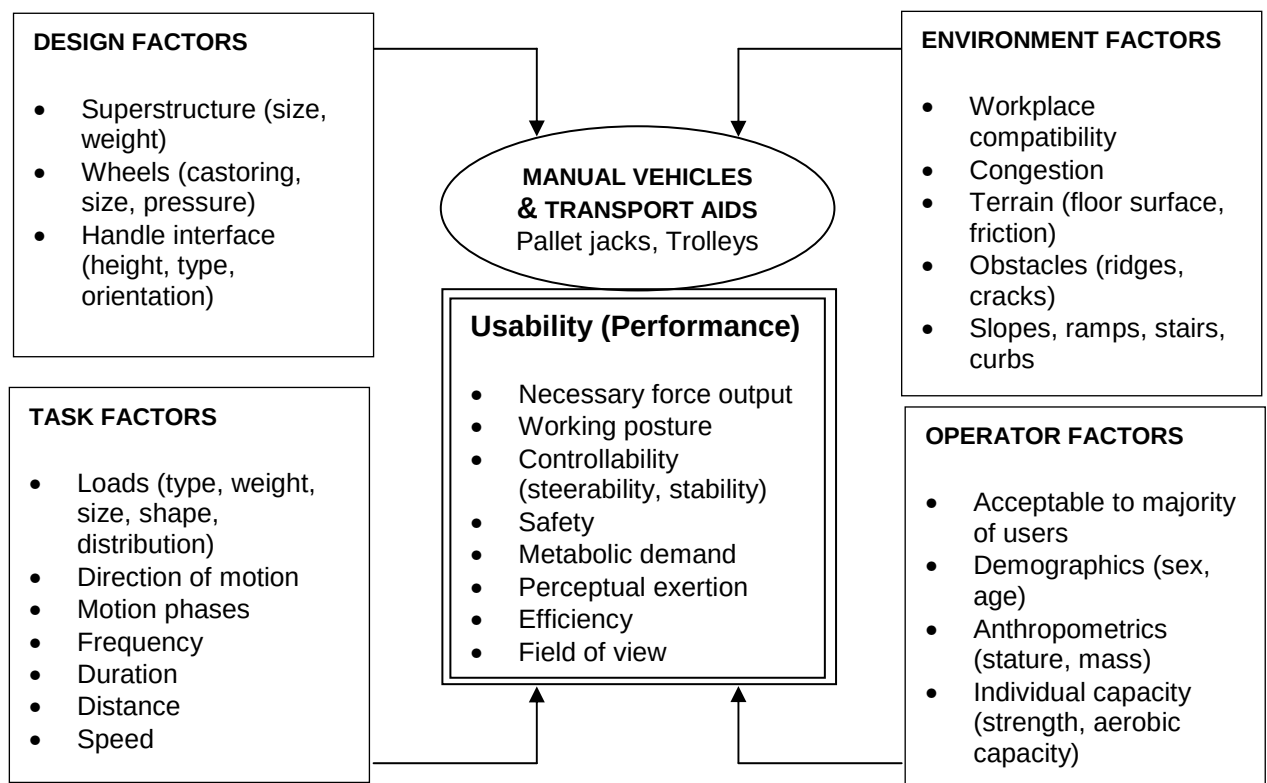


Figure 3. Factors influencing usability of manual vehicles (adapted from Mack **et al.**, 1995 and Jung **et al.**, 2005)

With the key objective of manual vehicles being to alleviate the workload and enhance usability, encompassing efficiency, safety, manoeuvrability, physical and psychophysical stresses, certain elements must be considered prior to their implementation. These include design, task, environmental and operator factors (Figure 3). It is important to note that these elements should not be considered in isolation from one another because changing one often necessitates changing another.

Design factors

Handle interface

Of all design factors, handle interface is the most extensively studied and most contentious with countless recommendations, largely due to the lack of standardised methodologies, differences in postures and measured responses. The interaction between the individual and interface determines the posture

adopted (Lee **et al.**, 1991), steerability and, in turn, force-producing capability (Chaffin **et al.**, 1983; Fothergill **et al.**, 1992; Kumar, 1995a; Mack **et al.**, 1995; Jansen **et al.**, 2002) as well as spinal loading (Lee **et al.**, 1991; Hoozemans **et al.**, 2004). Possibly the two most extensively used criteria are push/pull capability and spinal loading. In accordance, Imrhan (2003) aptly stated that handle interface can restrict the ability to exert a push or pull because an inferiorly-designed interface behaves “like a weak link in the chain of force transmission” (pp 23-2). In turn, this is likely to influence spinal loading, due to the reported relationship between these variables (Lee **et al.**, 1991; Jansen **et al.**, 2002). When determining the suitability of handle interface, it is pivotal to assess factors such as handle height, type and orientation.

Table II. Recommendations of handle height

Author	Year	Exertion	Criterion investigated	Recommendation
Martin and Chaffin	1972	Static	Push/pull capability	500-900mm
Ayoub and McDaniel	1974	Static	Push/pull capability	70-80% shoulder height
Chaffin et al.	1983	Static	Push/pull capability	680mm
Lee et al.	1991	Dynamic	Spinal loading	Push 1090mm Pull 1520mm
Snook and Ciriello	1991	Dynamic	Maximum acceptable forces	Push ♂ 950mm; ♀ 890mm Pull ♂ 640mm; ♀ 570mm
Fothergill et al.	1992	Static	Push/pull capability	1000mm
Gagnon et al.	1992	Dynamic	Spinal loading	Waist level
Kumar	1995a	Static & dynamic	Push/pull capability	Hip height
Resnick and Chaffin	1995	Dynamic	Spinal loading	Knuckle height
de Looze et al.	2000	Dynamic	Shoulder and spinal loading	70% shoulder height
Jansen et al.	2002	Dynamic	Force exertion	Shoulder height
Hoozemans et al.	2004	Dynamic	Shoulder and spinal loading	Shoulder height
James et al.	2005	Static	Push/pull capability	Iliac crest height
Pheasant and Haslegrave	2006	Unspecified	Unspecified	Between radiale & acromiale heights

Handle height or the vertical point at which force is applied is possibly the most litigious factor with reference to usability criteria for manual vehicles (Table II). Arguably, it is more important for four- as opposed to two-wheeled manual vehicles, with the latter allowing for varying degrees of tilting and hence adjustment of handle height and posture. However, both should promote the adoption of comfortable postures (Mack **et al.**, 1995). Provision of a single numeric recommendation is inappropriate for all conditions (Imrhan, 2003) and is almost impossible to achieve given the diversity and complexity of each work context.

Various vertical and horizontal handles are available for use in industry. Some authors have supported the use of the vertical type as they allow users to select handle heights and postures based on individual needs (Das **et al.**, 2002; Jansen **et al.**, 2002; Pheasant and Haslegrave, 2006). Das **et al.** (2002) specified that two vertical handles should be placed between 940mm and 1153mm above the ground. With the use of vertical handles however, cognisance must be taken of their distance apart to render them acceptable to most users. Although an optimal width for grasping is not achievable with the use of two vertical bars, they are considered to be mechanically sound when placed shoulder width apart, a claim as yet unverified (Jansen **et al.**, 2002).

An early study investigating the effect of operator stance on push/pull capability concluded that the preferable handle height for pushing or pulling was located between 70% to 80% of acromiale height (Ayoub and McDaniel, 1974). Some studies (Chaffin **et al.**, 1983; Fothergill **et al.**, 1992; Al-Eisawi **et al.**, 1999a) have found that when handles are placed higher, force producing capability decreases. Chaffin **et al.** (1983) attributed this to body posture and stated that at a high handle height the body is close to upright, whereas the lower height causes forward and backward leaning for pushing and pulling respectively. The upright stance constrains the turning moments about the feet, limiting force generation. In contrast, the forward and backward leaning results in higher turning moments about the rearward or forward foot, for push and pull respectively, creating higher forces.

Other studies have shown lower or intermediate (Davis and Stubbs, 1978; Kumar, 1995a) handle heights to be favourable. Davis and Stubbs (1978) recommended that higher push/pull forces are achievable at hip height compared to shoulder height or above. Similarly, Kumar (1995a) reported that isometric and isokinetic push/pull strengths across both sexes are optimal at 1000mm as opposed to 350mm or 1500mm. Data derived psychophysically (Snook and Ciriello, 1991) demonstrated that for pulling, forces were greatest at higher heights (950mm and 890mm for males and females respectively) while for pushing, they were greatest at lower heights (64mm and 57 mm for males and females respectively).

Discrepancies exist regarding handle heights and mechanical loading at the lower back or shoulders. According to de Looze **et al.** (2000), to minimise loading in these body areas, the handle interface should allow the resultant force to be close to horizontal, implying that higher handle heights are preferable. Many authors (Resnick and Chaffin, 1995; de Looze **et al.**, 2000; Hoozemans **et al.**, 2004) reported that the highest compressive forces experienced in the lower back occur when the trunk is flexed forward as when using a low handle height. Although Lee **et al.** (1991) found an intermediate height (1090mm) was desirable for pushing and a higher level (1520mm) was favourable for pulling, they cautioned that findings must be applied tentatively as slipping may result at the suggested handle heights. In a study by Hoozemans **et al.** (2004) shoulder height was recommended over hip height to minimise loading on the spine and shoulders, however an intermediate height was not investigated, which may have some bearing on the recommendation.

The size and shape of a handle differentiate between a well- and poorly-designed apparatus, with findings indicating that a poor interface reduces pulling strength by as much as 65% (Fothergill **et al.**, 1992). Typically, these factors dictate the type of grip adopted. According to Fothergill **et al.** (1992) the use of a horizontal bar, which allows for an overarm grip, is best suited for pulling capability. Although forces produced using a vertical bar were comparable, knuckle clearance was restricted and discomfort experienced. Importantly, handle height has less bearing on force production and performance in the case of poorer designs.

Although handle orientation is considered to be an important factor, it has not been studied with regard to four-wheeled vehicles. According to Okunribido and Haslegrave (1999) handle orientation has a direct impact on upper limb joint loading, affecting wrist posture. They concluded that for two-wheeled vehicles, a handle height of 1000mm and a handle angle of 35° from the vertical were optimal during the initial phase of motion. During the sustained phase of motion, although findings were unclear, they suggested that the optimal arrangement would most likely be geared towards a larger angle.

Posture and foot position

Ergonomists have for a long time suggested that 'good working postures' are integral for the efficient completion of a task, and have recognised that certain situations may encourage the worker to assume awkward or poor working postures. Consequently postural stress, pain and fatigue are experienced, with the worker only resuming work once the muscles have recovered (Corlett, 1981). As such performance may be hindered not by a person's physical capacity, but by pain (Corlett, 1981).

Handle height and placement of feet largely influence the posture adopted during pushing/pulling (Ayoub and McDaniel, 1974), affecting force output (Daams, 1993) and the stresses imposed on the body. It follows that without consideration of ergonomic principles in equipment design, poor or awkward working postures are likely, resulting in static loading and acute localised muscle fatigue (Das **et al.**, 2002), ultimately compromising health and safety (Haslegrave, 1994).

In general, forward and backward leaning is encouraged for pushing and pulling respectively, as body weight can be used to augment push/pull strength and effectively counteract the hand forces (Ayoub and McDaniel, 1974; Warwick **et al.**, 1980; Pheasant **et al.**, 1982; Chaffin **et al.**, 1983). In 1993, Daams concluded that 'free' postures, chosen by the subjects, permitted higher force generation during maximal unilateral static pulling and argued that free postures are more representative of the *in situ* milieu, whereas restricted postures do not allow for the extrapolation of data to field settings. Similarly Fothergill **et al.** (1991) argued that the result of most studies imposing postural constraints, particularly for static strength implies that results are more representative of the constrained conditions than of the individuals' actual strengths under free postures.

Considering foot position and force output, as a general rule, Pheasant and Haslegrave (2006) inferred that force exertion is strongest when the feet are placed as far back or as far forward as possible for pushing and pulling respectively. These guidelines should however be applied tentatively because the potential to slip increases under such conditions, therefore traction between the

shoes and floor is paramount (Pheasant and Haslegrave, 2006). With reference to foot placement, a staggered posture is optimal. The pivoting foot should be placed in front of or behind the body's centre of mass for pulling and pushing respectively (Ayoub and McDaniel, 1974; Warwick **et al.**, 1980; Pheasant **et al.**, 1982; Chaffin **et al.**, 1983). Ayoub and McDaniel (1974) recommended that for pulling, the leading foot be positioned at -10% of shoulder height from the plane of force exertion; for pushing the rear foot be placed at 100% of shoulder height from the plane of force exertion. Chaffin **et al.** (1983) also found that pushing strengths decreased by as much as 17% when the feet were symmetrically together for pushing. For pulling, no significant differences in strengths were evidenced between a staggered and symmetrical foot placement.

Wheels and castoring

Wheels and castoring determine the manoeuvrability of manual carts and trolleys, and hence influence a person's ability to generate force (Mack **et al.**, 1995). In confined spaces, wheels of smaller diameters allow for better manoeuvrability, but encumber steerability and the overall capacity to perform push/pull tasks (Mack **et al.**, 1995). Ordinarily, regardless of the criteria under examination, studies have found large diameter wheels to be preferable for most manual vehicles. Considering its effect on speed of motion, Drury **et al.** (1975) reported that wheels of 25cm diameter allowed for higher speeds compared with those of smaller diameter (7.5cm). While David and Nicholson (1985) demonstrated that larger wheels caused intra-abdominal pressure to be decreased by 43%, reducing stress on L₅/S₁, specific recommendations were not provided. Similarly, when assessing the effect of wheel diameter on force production, Al-Eisawi **et al.** (1999b) demonstrated an inverse relationship, whereby smaller diameter wheels caused large initial forces.

With specific reference to castoring, Mack **et al.** (1995) deduced that the ability of an individual to control and steer the vehicle was reduced when castors swivelled too freely, which seemingly increased the force requirement. The general consensus is that the selection of wheels is affected by flooring and should be

based on reducing rolling friction/resistance. As such, they should be hard, have high-pressure tyres and good bearings (Eastman Kodak, 1986; Das **et al.**, 2002).

Task factors

Load

A survey of several industries by Mack **et al.** (1995) concluded that the mass of loads transferred per trip varied from 2kg to 1500kg on a hand pallet truck with distances varying from a few metres to hundreds of metres. Frings-Dresen **et al.** (1995) found high variability in the mass of loads moved by refuse collectors, with a single individual displacing average loads of 22kg and 110kg for mini and large containers respectively on a working day, while a more recent study (St-Vincent **et al.**, 2005) concluded that in a superstore, the total cumulative load moved on a pallet jack daily may be as high as 4400kg. Despite the variability of the masses being moved, many authors have argued that regardless of vehicle type, load mass should be minimised to prevent excessive bodily stress (Lawson **et al.**, 1993; Resnick and Chaffin, 1995; van der Beek **et al.**, 2000), with the load's centre of mass situated as low as possible (Kingma **et al.**, 2003). Practical constraints do not however always allow load mass to be altered, thereby making consideration of ergonomic principles in the design of manual carts or trolleys imperative. A relatively simple solution advocated by Jung **et al.** (2005) is the use of light-weight materials in the construction of the vehicles.

Load mass is one of the principal factors to consider in the (re)design of push/pull tasks because it is known to greatly affect force output (Resnick and Chaffin, 1995; Donders **et al.**, 1997; Jung **et al.**, 2005; Todd, 2005; Cripwell, 2007; Bennett **et al.**, 2008). Resnick and Chaffin (1995) demonstrated that peak hand forces increased by as much as 184% when the load mass was increased from 45kg to 450kg. In the same investigation, loads of 225kg and 450kg were found to elicit compressive forces at the lower back in excess of the NIOSH limit of 3400N for the 'average strength' male, while a load of 450kg elicited similar responses for the 'strong' male. Although the sample in this study was small, consisting only of two males and two females, Resnick and Chaffin (1995) concluded that a worker's ability to displace the manual vehicle is an unsuitable measure of safety since

stronger workers can move heavy loads which may compromise the integrity of L₅/S₁. They recommended analyses of posture and hand force production as more suitable alternatives. This is warranted considering that higher hand forces have been alleged to coincide with increased spinal loading (Lee **et al.**, 1991; Jansen **et al.**, 2002) and mechanical loading of the shoulders (Jansen **et al.**, 2002). Although Resnick and Chaffin (1995) concluded that loads in excess of 250kg should be avoided, this recommendation is only valid under the 'ideal' conditions outlined in their study and any changes to it, such as decreasing shoe/floor friction, would likely decrease the load mass limit.

Numerous authors have demonstrated a linear relationship between load mass and hand forces (Donders **et al.**, 1997; van der Beek **et al.**, 2000, Cripwell, 2007; Bennett **et al.**, 2008). This suggests that the acceptability of forces can be assessed using regression equations and without workers having to move extremely heavy loads, thereby minimising the risk of overexertion. The linearity of the relationship is however only applicable to the context from which it was derived, and is not suitable for application to all situations.

Frequency and duration

Frequency and duration of pushing/pulling manual vehicles, shown to vary greatly between industries (Frings-Dresen **et al.**, 1995; Mack **et al.**, 1995; St Vincent **et al.**, 2005), are two key elements to consider when gauging exposure to these tasks (van der Beek **et al.**, 1999), particularly when assessing their physiological cost. In refuse collection, some manual vehicles are reported to be employed as much as 500 times daily for different periods of time (Frings-Dresen **et al.**, 1995), while in a superstore as few as 93 times in a five hour shift. The variability between industrial sectors suggests that recommendations developed from one are not necessarily applicable to others.

Eastman Kodak (1986) suggested that frequency of use of manual vehicles should be limited to 200 times daily. Such guidelines are however meaningless if the entire context is not taken into account. It is inconceivable that pushing a trolley of 500kg 200 times daily will impose the same stress as pushing a lighter vehicle of

50kg 200 times daily. Alternatively, it can be assumed that pushing a 50kg cart for 5 minutes is not comparable to pushing the same cart for one hour. It is clear that consideration of the interaction between variables is advisable and that such factors are not assessed in isolation.

Speed and distance

Recommendations for speed generally indicate that slow speeds are desirable (Eastman Kodak, 1986; Jung **et al.**, 2005), with Eastman Kodak (1986) suggesting speeds of less than 1.1ms^{-1} (3.96km.h^{-1}). Slow speeds allow for superior control over the vehicle, reducing the potential for injuries, specifically slip, trip and fall accidents. This was demonstrated in a study by Lee **et al.** (1991), who concluded that the risk of slipping increased when speed of pushing and pulling was in excess of 3.6km.h^{-1} . The ability to move loads at specific speeds is a function of strength capabilities, with Resnick and Chaffin (1995) concluding that stronger subjects are able to displace loads at higher velocities than weaker ones moving the same loads. Furthermore, speed affects the compressive forces experienced at the lower back, with an increase in speed causing greater compressive forces (Lee **et al.**, 1991; Resnick and Chaffin, 1995). As such stronger individuals who can attain high velocities to move loads also compromise the integrity of the lower back. Conversely weaker individuals unable to achieve such velocities, compromise performance, as demonstrated in their inability to complete the task.

A survey by Mack **et al.** (1995) found that the distances covered while performing industrial pushing/pulling tasks ranged considerably between 9m and 500m per trip. The recommended limits by Eastman Kodak (1986) suggested that 33m and 16m are acceptable for four- and two-wheeled carts respectively, indicating huge discrepancies between what is considered acceptable and what the 'real' situation demands. Even recommended values are questionable because usability is affected by other factors such as load mass and coefficient of friction between the wheels/floor and shoe/floor, emphasising the need to consider the matter in its entirety. For the purposes of the current research the selection of distance was based on the ability to differentiate between motion phases without fatiguing the participants.

Environmental Factors

Friction

Two categories of friction instrumental to safety guidelines have been identified, namely shoe/floor friction and wheel/floor friction or rolling friction (Jung **et al.**, 2005). The former is essential in determining slip potential (Chaffin **et al.**, 1983). When the maximum coefficient of friction (CoF), attainable by the worker as a result of shoe/floor coupling, is surpassed by the ratio of the friction force to the normal force at the feet, slipping occurs (Hoozemans **et al.**, 1998).

Previous literature concerning friction and pushing/pulling have been concerned with the impact of shoe/floor friction on hand force exertion, with the general conclusion being that the former will limit or enhance a person's ability to generate force (Boockock **et al.**, 2006). A number of studies have demonstrated that floors of lower coefficient of friction (CoF) result in lower hand forces (Drury **et al.**, 1975; Mack **et al.**, 1995; Al-Eisawi **et al.**, 1999b; Jansen **et al.**, 2002), reductions in maximum acceptable initial and sustained horizontal forces and maximum acceptable weights (Ciriello **et al.**, 2001, Ciriello, 2005). On the contrary, Haslam **et al.** (2002) and Boockock **et al.** (2006) found no significant differences between psychophysically determined maximum acceptable horizontal forces between a high and a low CoF surface for pushing and pulling. This was attributed to the individual's ability to compensate for low shoe/floor traction by modifying the direction of hand and foot forces and working posture. The implications for industry are profound, because any changes in floor friction may lead to differences in the way work is performed, leading to unfavourable loading on the musculoskeletal system (Haslam **et al.**, 2002; Boockock **et al.**, 2006). Thus floors of low CoF tend to result in low force outputs and concurrently increase the potential for slipping (Jung **et al.**, 2005), placing the worker in a potentially hazardous situation.

Other studies have assessed the interplay between CoF and other variables, highlighting the importance of not considering factors in isolation. Lee **et al.** (1992) demonstrated that to achieve comparable force outputs, the use of a lower handle height necessitated a high CoF of 0.98, while a higher handle height only required a CoF of 0.31. Additionally, Ciriello **et al.** (2001) and Ciriello (2005) argued that the

time taken to complete a task increases when the possibility of slipping increases, compromising the efficiency of the work process. Although no one situation has been found to be ideal, hard and dry floor surfaces are preferred (Drury **et al.**, 1975; Laursen and Schibye, 2002), with 0.4 to 0.6 CoF being recommended (Sotter, 1995).

Gradient

Literature surrounding pushing/pulling of manual vehicles along ramps is still inadequate, yet these activities frequently occur. Despite this, it is well known that uphill efforts place great strain on the musculoskeletal system, with Glitsch **et al.** (2007) and Jäger **et al.** (2007) reporting that hand forces and spinal loading respectively may be problematic. Suggested limits for ramps have been in the region of 2% (Eastman Kodak, 1986; Lawson **et al.**, 1993) and they are preferred over stairs and curbs. More so, level exertions are less demanding than graded ones, yet it is unclear whether uphill or downhill exertions impose the least stress biomechanically and perceptually (Desai, 2006). Level efforts are therefore optimal but if slopes are necessary they should be maintained as close as possible to the horizontal. In this way, the additional effort to overcome the effect of gravity from uphill and downhill pushing/pulling, is negated (Bennett **et al.**, 2008).

Operator Factors

Gender and anthropometric differences

It was ascertained that of twelve industries, the majority (68%) of cart users were males (Mack **et al.**, 1995). With the introduction of labour laws to protect the right of females to occupy these jobs however, a large proportion of women are becoming involved in physically demanding work, yet guidelines specific to females are lacking. This is problematic as females executing the same workload as males would endure higher muscular and metabolic strain, as a result of sex differences (van der Beek **et al.**, 2000). Considering overall strength, females are approximately two-thirds as strong as males (Gallagher and Moore, 2003) and are therefore incapable of generating comparable forces (Resnick and Chaffin, 1995; Hoozemans **et al.** 1998). The female/male strength ratio during pushing/pulling also varies considerably (0.5-0.9) depending on posture and type of strength

(Fothergill **et al.**, 1991; Kumar **et al.**, 1995). Less inequality, demonstrated by higher ratios, is evidenced when the legs contribute more to the effort, occurring when pulling at lower handle heights (Fothergill **et al.**, 1991) or when strengths are generally weaker, such as when directing efforts in planes other than the sagittal (Kumar **et al.**, 1995).

Although sex differences exist, some findings may be better attributed to differences in anthropometrics such as stature and mass (Fothergill **et al.**, 1991; van der Beek **et al.**, 2000). Variables such as body mass and stature influence the postures adopted and the way tasks are completed, affecting push/pull capability. Increases in body mass (Ayoub and McDaniel, 1974; Chaffin **et al.**, 1983; Lee **et al.**, 1991) and stature (van der Beek **et al.**, 2000) augment the forces generated. Body mass is particularly pertinent to consider, specifically when used to manipulate force directly, such as in forward and backward leaning during pushing and pulling respectively (Kroemer, 1969; Ayoub and McDaniel, 1974). A study by van der Beek **et al.** (2000) determined the presence of differences with and without corrections for personal factors such as stature and body mass. Without corrections, differences between the sexes were evident in all variables, but with corrections, only differences between average and ending forces were significantly greater for males than females. There were no sex differences between the initial forces when corrections were made. It was reported that responses were influenced by technique, motivation or experience and not by the personal factors (van der Beek **et al.**, 2000). Other authors concur, reporting that technique is paramount in task execution (Lett and McGill; 2006; Bennett **et al.**, 2008) and additionally that experience affects the stress imposed, with more experienced individuals being able to minimise lower back stress and demonstrating more efficient muscle use indicated in lower muscle activity (Lett and McGill, 2006).

Unilateral and bilateral exertions

Hoozemans **et al.** (1998) argued that use of one or two hands is an important factor to acknowledge with regard to lower back and shoulder loading. It must also be considered with regard to push/pull capability. Overall, bilateral exertions are preferable to unilateral ones in minimising the risk of injuries (Das **et al.**, 2002) and

enhancing performance. Chaffin **et al.** (1983) found that push/pull strength was significantly greater for bilateral as opposed to unilateral exertions, with the pushing forces increasing the most, from 201N to 302N, and pulling ones from 198N to 235N. On the contrary, Fothergill **et al.** (1991) and Imrhan (2003) argued that there is very little difference between unilateral and bilateral exertions. Fothergill **et al.** (1991) reported that at lower handle heights, two-handed forces usually exceeded those of one-hand, but as handle height increased, unilateral strengths approached and under some circumstances exceeded bilateral ones. This was attributed to the fact that push/pull capability is not solely derived from the arms and that one-handed exertions allow for more freely chosen postures, permitting more effective use of body mass and centre of gravity. Importantly, with the use of only one-arm, the load-bearing shoulder may be exposed to stresses twice those of bilateral exertions, increasing the risk of injury (Fothergill **et al.**, 1991).

PERCEPTUAL ASPECTS OF PUSHING AND PULLING

Gamberale (1985) argued that perceptual aspects of performance were previously disregarded largely because they are subjective and cannot be directly measured. Their usefulness has however been acknowledged as they have been shown to correlate with task intensity and performance (Gamberale, 1985). According to Borg (1978) perceptual ratings should accompany the more objective tangible measures if science is to fully understand an individual's capacity for work. In essence, these tools are employed to enable individuals to recognise safe work limits and subsequently perform within them (Monahan, 1988), yet subjective measures are not widely implemented. To attain an indication of what the operator is willing to do, and not only what he can do, perceptual strain must be assessed.

Body Discomfort Scale

One of the most well-recognised perceptual tools was developed by Corlett and Bishop in the 1970s. In 1976, they introduced the concept of a "*body discomfort scale*", used to gauge an individual's subjective feeling of discomfort while executing a task, based on the premise that the adoption of less than optimal working postures causes pain. The resulting pain is indicative of a disturbance in

the equilibrium of compatibility between the worker and the job requirements. Corlett and Bishop (1976) realised that redesigning tasks to make workers more comfortable is beneficial to the organisation and is reflected in an improved work output through the reduction of the length of non-working time, thereby increasing working time with a reduced physical load.

The scale consists of two body maps (Appendix B), representing the anterior and posterior as well as the right and left aspects of the human body. Each map is divided into 28 segments, each numbered and representing a specific body region. Having selected the body region(s) experiencing the most discomfort, individuals are required to select an intensity rating, from an accompanying Likert-type rating scale, ranging from 1 to 10, with one denoting 'very slight discomfort' and 10 being 'very uncomfortable'.

Although the implementation of the scale is relatively easy, the subjective aspects make results difficult to interpret, primarily because participants may not fully understand their use. Perhaps it is for this reason that few researchers have opted to use these scales specifically for pushing and pulling investigations. Using a modification of the body discomfort scale, the body contribution scale, James **et al.** (2005) identified that the shoulders and lower back play a significant role in maximal pushing, and that the shoulders, biceps and triceps contribute to maximal pulling efforts. In more recent studies, Bennett (2006) and Desai (2006) found that the deltoids, biceps, calves and quadriceps significantly contribute to submaximal dynamic pushing/pulling activities. Bennett (2006) further reported that the hamstrings and triceps were subjectively rated as being involved. Using these as indices, the upper body and lower back are areas of concern.

TO PUSH OR PULL?

Despite the gaining momentum of research into pushing and pulling, there is no definitive agreement as to which is more acceptable in terms of safety and efficiency. Biomechanically pushing is generally considered preferable (Todd, 2005) however, physiologically and perceptually, this claim is unverified because neither has been researched extensively. Since the majority of literature surrounds

the biomechanical field, some authors like Lee **et al.** (1991) have used spinal loading as an indicator to identify which is optimal, concluding that pushing elicits lower stress at L₅/S₁ than pulling. Most often however, hand force exertion has been used. In Table III are findings demonstrating whether pushing or pulling is optimal based on which permits the higher push/pull capability. The table highlights the large variability in the literature, with no conclusive evidence to support a single recommendation despite all being based on measures of hand force exertion.

Table III. Preference for push/pull based on hand force exertion

Author	Year	Exertion	Preference Push/pull capability
Snook	1978	Dynamic	Push
Warwick et al.	1980	Static	Push
Snook and Ciriello	1991	Dynamic	Push
Daams	1993	Static	No difference
Lawson et al.	1993	Dynamic	Push
Kumar	1995a	Static & Dynamic	Pull
Kumar et al.	1995	Static	Pull
Al-Eisawi et al.	1999a	Dynamic	Pull
de Looze et al.	2000	Dynamic	Push
van der Beek et al.	2000	Dynamic	Push
James et al.	2005	Static	No difference
Lett and McGill	2006	Dynamic	Push

Disparities may be due to differences in methodologies such as posture or restrictions on postures (Al-Eisawi **et al.**, 1999a). Some studies focused on static tasks and others on dynamic activities, some on maximal exertions and others on submaximal efforts. Similarly, differences in the direction of motion (forward pushing, forward pulling, backward pulling) may have resulted in conflicting recommendations. This necessitates a need to investigate these tasks as they occur in industry, taking cognisance of the many factors that interact to affect the variables of interest.

SPINAL KINEMATICS

Introduction

Although injuries to the lower back have afflicted the human race for centuries, researchers have failed to identify a definitive cause (Snook, 1978), with risk factors being personal and occupational (Marras, 2000; Pheasant and Haslegrave,

2006). The former refers to anthropometric and demographic information specific to the individual; the latter to attributes of the job, such as psychosocial factors (Marras, 2000) and biomechanical stresses imposed on the worker (Pheasant and Haslegrave, 2006). In reality the risk factors do not behave in isolation but are interactive, rendering the situation much less clear (Marras, 2003a; Pheasant and Haslegrave, 2006).

Evidence provided through aetiological investigations (Pope, 1989) suggests that the nature of work may be indicative of the degree of risk of suffering a LBD. In particular, MMH tasks, and more specifically lifting, are related to lower back morbidity (Marras **et al.**, 1995; Lavender **et al.**, 1998). In spite of pushing and pulling also being mentioned as risk factors (Lee **et al.**, 1989; Marras **et al.**, 1995), minimal effort has been made to substantiate this claim. Apart from job type, some individuals are genetically predisposed, with some workers never falling victim to LBP irrespective of their occupation, while others become casualties in spite of the job roles they assume (Snook, 1978).

LBDs are estimated to comprise approximately 20% of occupational injuries (Marras **et al.**, 1995), yet are responsible for 33% to 41% of total costs of all compensation expenditure (Spengler **et al.**, 1986; Webster and Snook, 1994; Marras, 2003b). Notwithstanding the physical suffering to the worker, Marras (2000) reported that costs incurred are in the region of U.S.\$100 billion per annum. Evidently, technological advances and attempts to minimise manual labour have not reduced the incidence of LBDs.

Historically, symmetric MMH activities in the sagittal plane have been at the core of academic investigations (Marras **et al.**, 1995); yet they do not comprise the majority of tasks performed in the industrial setting (Drury **et al.**, 1989). Due to a failure to apply fundamental ergonomic principles in many job settings, workers often find themselves being forced to adopt awkward and uncomfortable working postures, suggesting that asymmetrical tasks such as one-handed pulling are common. These tasks frequently cause shear and torsion forces in the vertebral column and are linked to motion between the vertebrae. Traditional approaches

have however been concerned with static trunk positions, focusing primarily on compressive forces because previous literature alleges them to be the main factor contributing to LBDs (Granata and Marras, 1999). The problem is that a definitive causal relationship between the two has yet to be established (Granata and Marras, 1999). Clearly studies focusing on trunk kinematics during push/pull tasks are necessary if the mechanisms underlying LBDs are to be understood.

Biomechanical Logic

Both internal and external forces act on the intervertebral discs, apophyseal joints and other supportive structures during spinal loading (Ferguson **et al.**, 1992) (Figure 4), together accounting for the total force acting at the joint. The external forces are attributed to the force due to gravity acting on the individual and the load being displaced (Marras, 2000; Marras, 2003c), that is the mass of the load, together with that of the head, arms and trunk. The internal forces refer to those generated by the body in response to the external forces to maintain equilibrium, such as those produced by muscles, together with forces due to connective tissue (Marras, 2000; Marras, 2003c). In order to accurately predict spinal loads, Marras (2000) and Chaffin (2003) added that gauging the internal forces necessary to support the external forces is critical. This is because internal forces are often much greater than external ones as the human body functions at a distinct mechanical disadvantage, with the end result being that the internal load is the most influential factor in cumulative trauma (Marras, 2003b).

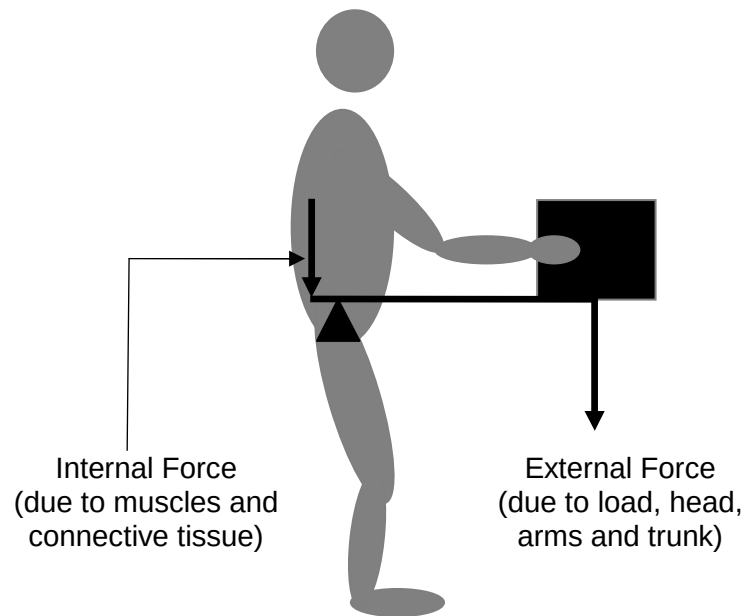


Figure 4. Forces acting on the spine (adapted from Marras, 2000)

Spinal loading occurs in the three cardinal planes (sagittal, lateral and transverse), giving rise to three different loading components: compression, shear and torsion (Marras, 2000), shown in Figure 5. According to Adams and Dolan (1995) these forces are not usually discrete but occur concurrently. Although compression has received the most scientific attention, all three are generally accepted as factors contributing to LBDs (Granata and Marras, 1999).

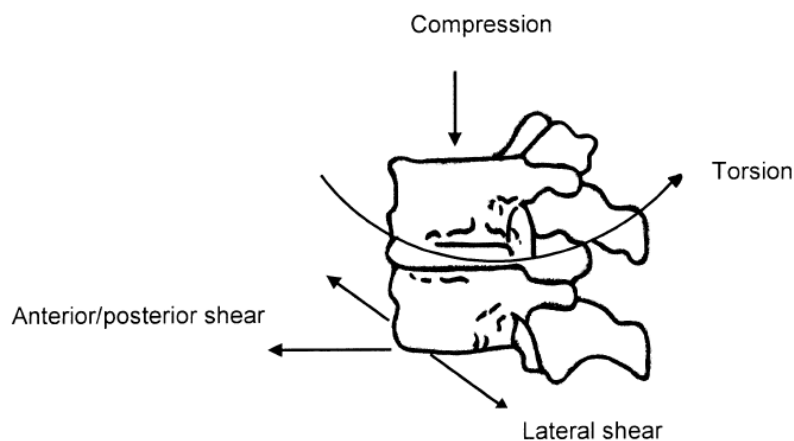


Figure 5. Loading components on the spine (Marras, 2000)

Consideration of these forces is pivotal to the principle underlying biomechanical logic, which states that when the spinal load exceeds the tolerance or strength

limits of the spinal tissues, injury is likely (Cholewicki and McGill, 1996). An acute or variable load exceeding the failure-tolerance of the tissue (Figure 6b) or sub-failure cumulative loadings which eventually reduce tissue tolerance (Figure 6c) may result in trauma (McGill, 1997; Marras, 2000, Marras, 2003a). Alternatively, injury may arise from a combination of the two (Marras, 2000). Work is considered safe when the spinal load is maintained within the safety margin (Figure 6a), defined as the difference between the tolerance limit and applied load (McGill, 1997). It is important to note that injuries to the lower back are not necessarily caused by very high loads, but also by repetitive low loads (McGill, 1997). The load-tolerance relationship is therefore an indicator of the risk of LBDs (Marras, 2003a) and infers that LBDs may be mechanical in origin (Marras, 2000).

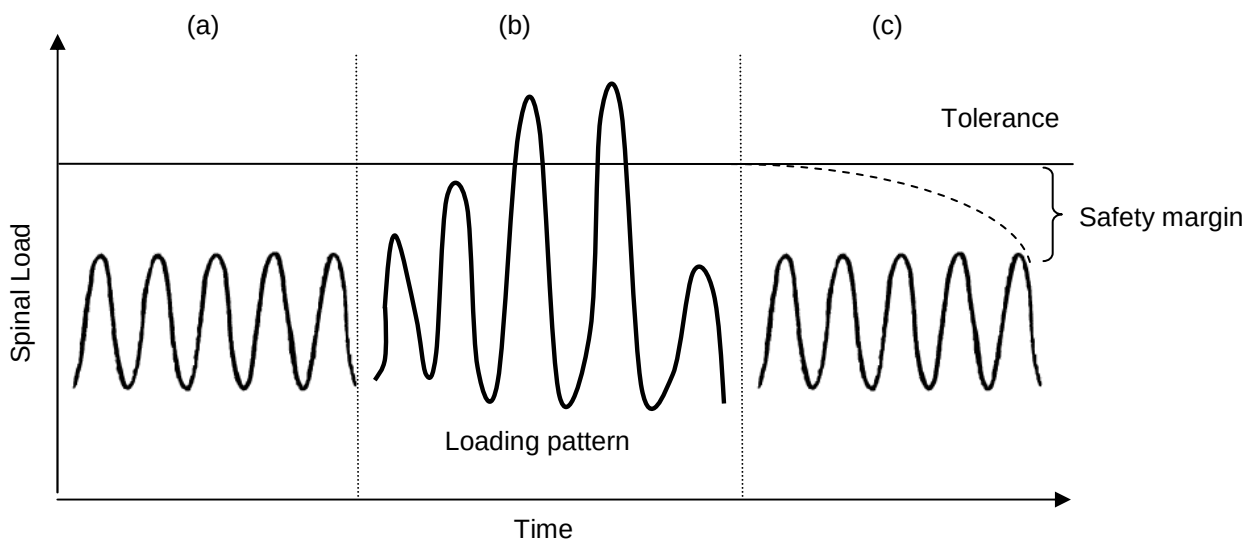


Figure 6. Load-tolerance relationship (adapted from McGill, 1997 and Marras, 2000)

- | | |
|-------------------------------------|-------------|
| a) Load < Tolerance | → Safe Work |
| b) Increased variability in loading | → Trauma |
| c) Reduced tolerance over time | → Trauma |

Tolerance limits differ for compression, shear and torsion (Marras, 2003c), and have generally been found to be lower for the latter two (Marras, 2000). They appear to be affected by cyclic loading, time of day, hydration and posture during loading (Marras, 2000). According to NIOSH (1981) compressive loads should be maintained below 3400N to prevent microfractures of the vertebral endplates. For

pushing/pulling studies specifically, compression forces have been in the region of about 2000N (Lee **et al.**, 1991; de Looze **et al.**, 1995; Resnick and Chaffin, 1995; Schibye **et al.**, 2001).

Shear force tolerance limits for the lumbar spine are variable, with Farfan **et al.** (1970) reporting 1735N, McGill (1997) 1000N and more recently, Yingling **et al.** (1999) 2500N based on a porcine investigation. Literature surrounding torsion forces is practically non-existent, despite its apparent role in LBDs. Importantly, it has been reported that when loading occurs simultaneously in many planes, tolerance of the lumbar segment is reduced (Shirazi-Adl, 1989).

Assessment of Spinal Loading

Numerous assessment tools have been developed in efforts to quantify the risk of lower back injuries associated with MMH activities (Mirka and Shin, 2006) and are highlighted in Table IV. They are often classified as static/dynamic and/or two/three- dimensional, with the aim being to predict the stresses imposed on L₅/S₁, to minimise the risk of injury.

Static Assessment

Previously, spinal loading was evaluated using static assessment tools and focused on lifting activities, yet Marras **et al.** (2003) elucidated that they neglect the effect of motion as a possible hazard in the causation of LBDs, with numerous authors (McGill and Norman, 1985; Granata and Marras, 1999) reporting that they tend to under-predict dynamic spinal compression by as much as 20% to 40%. According to Rodrick and Karwowski (2006) static models are limited because they fail to account for acceleration and assume a slow and smooth action, ignoring inertial effects, yet in reality supplementary forces are required to overcome inertia to accelerate or decelerate objects being displaced.

Initial approaches to gauge the internal forces due to the muscles assumed that a single equivalent muscle force could be used (Marras, 2003c). However, these oversimplified the situation considerably, failing to acknowledge that many muscles are active. A major drawback of the early approaches was that muscle

co-contraction was neglected (Marras, 2005) yet it is associated with an increase in spinal loading (Granata and Bennett, 2005). The result is that compressive and shear forces were frequently under-estimated, by as much as 45% and 70% respectively (Granata and Marras, 1995). This is particularly important considering that instability of the trunk tends to amplify co-contraction (Granata and Orishimo, 2001), implying that dynamic pushing/pulling may affect co-contraction (Lee and Granata, 2006). According to some reports, the application of single equivalent muscle models to pushing and pulling activities is low (Andres and Chaffin, 1991; Lee **et al.**, 1991). Following this, multiple muscle systems, which are more representative (Schultz and Anderson, 1981) were developed but because over ten muscles provide internal support to the external load, researchers were forced to make unrealistic assumptions about which muscles were active (Marras, 2000).

One of the most widely applied tools was developed by the National Institute for Occupational Safety and Health (NIOSH) in 1981, called the NIOSH Lifting Guide. Although originally aimed at minimising the risk of MSDs in general, it has been widely implemented to reduce back injuries (Marras **et al.**, 1999). Biomechanically, one of cornerstones upon which it is based is the assumption that compressive forces acting on the spine are the root cause of LBDs (Granata and Marras, 1999). As such, if a given task results in less than 3400N of compressive spinal loading, it is considered safe, while any task that imposes more than 6400N is considered to place that worker at high risk. Although allegedly founded on biomechanical, physiological, and psychophysical criteria (Marras **et al.**, 1999), it has been heavily criticised, with Jäger and Luttman (1999) suggesting that the 3400N criterion is not validated either biomechanically or epidemiologically. Since it is only applicable to lifting tasks performed in the sagittal plane (Ferguson **et al.**, 1992; Waters **et al.**, 1993; Marras, 2003b), a revised equation was introduced in 1991, and was extended to incorporate asymmetric lifting tasks in other planes (Waters **et al.**, 1993), allowing for the assessment of a wider array of activities. The most fundamental limitation of both equations is that they are solely applicable to lifting and do not take into account the diversity of tasks in work settings.

Biomechanical models, such as the three-dimensional static strength prediction programme (3DSSPP), developed by the University of Michigan, can be used to estimate spinal compression and shear as well as the percentage of the population capable of performing a specific task based on strength (Mirka and Shin, 2006; Rodrick and Karwowski, 2006). It is however restricted to heavy manual work, involving slow movements, since they can be divided into a series of static postures (Järvinen and Lu, 2003) and cannot be used reliably to assess highly repetitive tasks or highly dynamic motions (Rodrick and Karwowski, 2006). The strength norms used as limits in the models are derived from young population groups, in the range 18 to 49 years and therefore have limited applicability to older individuals (Chaffin, 2003). Yet, in spite of these limitations, it is inexpensive, easy to use and can be employed to assess numerous low acceleration activities.

Table IV. Static and dynamic assessments of spinal loading

	Assessment technique	Limitations	Strengths
Static	Single Equivalent Muscle Models	Simplistic, unrealistic-assumes single equivalent extensor muscle force in trunk	Assisted in identifying necessity for multiple muscle system representation
Static	Multiple Muscle System Models (Schultz and Andersson, 1981)	Difficult to determine which muscles support external load and to quantify internal forces- Unrealistic assumption of which muscles are active	Acknowledges muscle co-activation
Static	NIOSH Lifting Guide (1981) Revised NIOSH Lifting Guide (Waters <i>et al.</i> , 1993)	Epidemiologically and biomechanically unsubstantiated Only applicable to lifting, with no considerable acceleration Poor predictive ability of risk	Based on biomechanical, physiological and psychophysical data Simple application
Static	Static Strength Prediction Programs (e.g. 3-dimensional SSPP)	Acceleration and momentum unaccounted for	Can simulate high exertion tasks during early part of design process, avoiding costly prototypes/retrofits Simple application Estimates mechanical forces on the musculoskeletal system
Static/ Dynamic	Biologically Assisted Models (Marras and Granata, 1997)	Require significant instrumentation, processing time Not predictive in nature	Does not rely on predicting active muscles, biological output monitored directly 3-D loading of spine under dynamic conditions Ability to assess individual unique spinal loading characteristics
Dynamic	Trunk Motion Models (e.g. Lumbar Motion Monitor Risk Model)	Mock up of workplace necessary	Considers dynamic motion in all three planes; ability to assess current and expected risk

Dynamic Assessment

In an attempt to circumvent problems associated with static models, biologically assisted models were developed (Marras, 2003b; Marras, 2003c; Marras, 2005). Marras (2006) emphasised the need to account for muscle co-contraction due to the high prevalence of dynamic motions in industry, and suggested the use of biologically assisted models, the most common of which makes use of electromyography. Use of these models means that there is no need to predict which muscles are active because their biological output is monitored directly (Marras, 2000), and muscle recruitment specific to the individual performing manual work is accounted for (Marras, 2006). Through direct assessment of the muscles, internal muscle forces and hence loading on the lumbar spine can be gauged (Marras, 2006). For this reason they are the most accurate tools available, but require the use of substantial equipment and time (Marras, 2000).

Trunk motion

Literature suggests that work intensity, static work postures, repetitive activities and frequent bending and twisting are closely related to the proliferation of vocational LBDs (Bigos **et al.**, 1986; Marras **et al.**, 1995) and infers that trunk motion is a possible contributing factor (Davis and Marras, 2000). Newton's Second Law ($\text{Force} = \text{mass} \times \text{acceleration}$), which implies that an increase in spinal acceleration will increase the spinal forces (Ferguson **et al.**, 1992), may lend credibility to this claim. Trunk motion was however previously overlooked because of the difficulty associated with measuring its elements in industry (Marras **et al.**, 1995) and possibly because tools aimed at measuring dynamic trunk motion are not widely available (Marras, 2006). With regard to this, Hindle **et al.** (1990) stated:

"The spine is a complex three-dimensional structure and it should thus be expected to undergo complex movements in three-dimensions....Ideally a measurement system should therefore measure the three-dimensional kinematic behaviour of the spine." (pp 219).

Ferguson **et al.** (2004) argued that direct measures of the factors encompassing trunk kinematics are perhaps the best measures for prediction models. One such

instrument, the Industrial Lumbar Motion Monitor (iLMM), is capable of directly quantifying spinal kinematics (Ferguson **et al.**, 2004). It mimics motion of the thoracolumbar spine, providing information pertaining to its instantaneous position, velocity and acceleration in the three cardinal planes (Allread **et al.**, 2000; Ferguson and Marras, 2004). A key advantage is that it is easily employed *in situ* while workers execute industrial tasks (Marras and Allread, 2005). Using information derived from this instrument, Marras **et al.** (1993; 1995) were able to develop a model capable of identifying tasks that place workers at high risk of LBDs, namely the Low Back Disorder Risk Model or Multivariate Approach.

Low Back Disorder Risk Model

Marras and colleagues (1993; 1995) postulated that a combination of trunk motion and task characteristics may be able to better identify exposure to risk of LBDs in repetitive MMH activities. These factors, identified as maximum moment, frequency, maximum sagittal flexion, average twisting velocity and maximum lateral velocity, are at the core of the Low Back Disorder Risk Model. Together they are instrumental in distinguishing between tasks of high and low risk, thereby contributing to the model's predictive power (Allread **et al.**, 2000), which has been reported to be 10.7 times better than chance (Marras **et al.**, 1993). Although the individual factors cannot reliably discriminate between tasks of low and high risk, an increase in one will increase the risk of incurring lower back morbidity (Marras **et al.**, 1993; 1995). Equally important then is that reducing any of the five risk factors will reduce the risk (Marras **et al.**, 1995). In 2000, Marras **et al.** evaluated how well the model could predict changes in LBD injury rates as the physical conditions to which employees were exposed changed, by comparing predictions with actual incidences. They concluded that a significant correlation existed between the two, and were hence able to validate the model.

Within industry, the model is able to predict LBD risk for individual tasks, following which the most hazardous tasks can be identified (Marras **et al.**, 2003). It can also be employed to monitor re-designed tasks, quantitatively comparing LBD risk pre- and post-intervention, a method that allows for immediate feedback (Marras **et al.**, 2000). It is not however without its limitations. Since it was developed using

datasets from repetitive jobs, it is inherently limited to these tasks and non-repetitive activities are not necessarily represented (Mirka and Shin, 2006).

MUSCLE ACTIVITY

Electromyography (EMG) is an invaluable tool, which can be used to indicate whether a muscle is active, determine muscle force or function as an index for muscular fatigue (Marras, 1992). The recruitment and firing rate of motor units within a muscle alter the electric signal, therefore an enhanced force requirement increases motor unit recruitment and firing frequency of the already recruited units (LeVeau and Andersson, 1992), demonstrated in an increase in myoelectric signal (Göbel, 2005). The onset of localised muscle fatigue, sometimes shown to be as low as 5% when the contraction is sustained for one hour (Sjøgaard **et al.**, 1986) and 10% for prolonged static work (Redfern, 1992) of the maximal voluntary contraction (MVCs) is reflected in frequency spectral shifts and an increase in signal amplitude. Göbel (2005) reported that electromyography is achieved either by needle or surface electrodes. The former are invasive as they are inserted into the muscle belly, while surface electrodes are placed on the surface of the skin. Although more commonly employed, caution must be exercised when using surface EMG as only muscles directly under the skin can be assessed and cross-talk from other muscles may cause interference (Göbel, 2005).

The investigation of muscle activity during pushing/pulling of manual vehicles has been ignored in the literature, yet its significance as a key research area must be acknowledged, bearing in mind that self-reports have identified the back and upper extremities as experiencing pain or discomfort during these activities (Hoozemans **et al.**, 1998; Hoozemans **et al.**, 2002). Jonsson (1988) reported that within industry, static loading of the shoulder musculature is a considerable problem and furthermore Ferreira **et al.** (2004) argued that the weakest muscles, generally associated with shoulder actions, tend to work at a higher percentage of their maximal capacity, and are likely to fatigue earlier. Clearly this is an area requiring further investigation. Muscle activity, specifically of large muscle groups impacts the strain experienced by the cardiopulmonary and musculoskeletal systems (Hoozemans **et al.**, 1998). This has important implications for pushing and pulling

since they generally involve the whole-body, comprising static muscular contractions, primarily evident in the trunk and upper extremities (Garcin **et al.**, 1996; Hoozemans **et al.**, 1998) as well as dynamic contractions occurring as an individual propels the manual vehicle forward during walking.

During pushing and pulling, trunk muscles are often studied, while peripheral body muscles are not usually afforded the same attention, possibly because trunk muscle activity is considered an index of spinal load (Kumar, 1995b), specifically reported to contribute to compression and shear forces in the spine (Song and Chung, 2004). Davis and Marras (2000), in a review of the effect of motion on trunk biomechanics, found that agonistic and antagonistic muscle activity increased with greater dynamic trunk motion, with the antagonists being affected more. This suggests that co-contraction of the trunk musculature increased, in turn accentuating the spinal load. This however occurred with no additional force producing capability since the antagonists do not contribute to force generation.

Kumar (1995b) was concerned with EMG of rectus abdominis, external obliques and erector spinae during garden raking. He concluded that pushing leads to an increased muscle load compared to pulling and that that erector spinae contributes considerably to both pushing and pulling actions. On the contrary, Lee **et al.** (1989) reported high muscle activity in rectus abdominis during isometric pushing but not pulling, while the opposite was true of erector spinae. Despite this, findings must be applied tentatively since their sample group was small, consisting of only two males and two females, and given that muscle activity is highly variable between individuals (Göbel, 2005). More recently, Anders **et al.** (2004) highlighted sex differences showing that the muscle activation of stabilising muscles in men were lower than in women while executing isometric shoulder exercises. Conversely the muscle activation in the muscles acting in the primary force direction was greater, implying that males are at a greater risk of damaging the shoulder girdle, an important finding considering that this body part is instrumental in pushing/pulling.

It has been reported that load mass has an impact on muscle recruitment (Davis and Marras, 2000). Søgaaard **et al.** (2001) investigated the muscle activity on the upper body specifically looking at the lower trapezius, medial deltoid and infraspinatus on both sides of the body while participants performed mopping and scrubbing tasks, typically involving push/pull motions. They found that generally the heavier cleaning devices elicited higher muscle responses. Similarly, Gallagher **et al.** (2002) reported an increase in trunk muscle activity in all muscles under investigation with an increase in load during a lifting task.

It is important to note that muscle activity changes according to the origin of effort, and therefore muscle activity will not be the same on both sides of the body during asymmetrical tasks. In the study by Kumar (1995b), the effort 'driving' completion of the task was the left side of the body, and as such muscles on the left incurred greater activity than those on the right during pulling. Conversely, due to the change in direction during pushing, muscle activity was higher on the right (Kumar, 1995b). These findings were corroborated by Søgaaard **et al.** (2001), who reported that during mopping and scrubbing, the arm, 'driving' the muscular effort, elicited higher muscle activity than the contra lateral side.

In 2005, Illyés and Kiss not only compared the muscle activity of the upper extremities during pushing and pulling, but additionally determined differences in muscle activity between experienced and inexperienced individuals, using a classification system according to the level of muscle activation. While the muscles employed by the experienced group were also employed by the inexperienced group, additional muscles used by the inexperienced group were not active in the experienced group for pushing and pulling. This implies that experienced individuals are able to induce lower levels of muscle activation than inexperienced ones. Muscles found to be either moderately or highly active in both groups during pulling included the posterior deltoid, infraspinatus and triceps brachii, while during pushing the anterior deltoid, pectoralis major, medial deltoid, infraspinatus and biceps brachii were involved.

CONCLUSION

The literature is clear in highlighting that a considerable proportion of MSDs are associated with pushing and pulling, yet the use of manual vehicles remains a necessary part of industrial work. Despite their frequent use, few comparisons between push/pull techniques have been initiated to identify which is related to a greater stress on the human operator, particularly in terms of lower back and upper body stress, areas that typically experience injury. Where comparisons exist, most were concerned with symmetric two-handed exertions in the sagittal plane as opposed to asymmetric one-handed exertions, which are commonly adopted.

Within the broad area of pushing and pulling, a vast majority of the research surrounds the factors affecting an individual's ability to exert hand forces to propel a manual vehicle, as these have been linked to LBP (Lee **et al.**, 1991; Jansen **et al.**, 2002). However inadequate attention has been afforded to the contributing role that spinal kinematics may play in lower back pathologies during push/pull activities. Furthermore, in the limited literature that exists on myoelectric activity of those muscles employed in pushing/pulling efforts, the primary area of concern has been on the stabilising trunk musculature (Lee **et al.**, 1989), while a number of other muscles that facilitate movement such as the shoulder muscles have largely been ignored but may also take strain (Bjelle **et al.**, 1981; Tola **et al.**, 1988).

Evidently there are significant gaps in the body of knowledge regarding pushing and pulling, necessitating investigation into the impact of different push/pull techniques and load masses on trunk motion characteristics and muscle activity of the upper body, together with measures of the forces exerted at the hands. To gain a more comprehensive understanding of the demands of these tasks and make relevant recommendations, it is appropriate to take a multifaceted approach as opposed to relying on a single criterion. The current study was thus not only concerned with biomechanical measures, but also perceptual ratings of body discomfort.

CHAPTER III

METHODOLOGY

INTRODUCTION

Despite the increased research into pushing and pulling, there are still discrepancies in the literature, largely a result of fundamental differences between methodological protocols and research objectives. Daams (1993) confirms this, stating that standardised postures are usually adopted intra-study, yet they vary between studies, making inter-study comparisons challenging. Comparisons become difficult when fundamental differences exist, such as findings derived from static tasks being applied to dynamic situations. This renders them unreflective of the 'real' milieu thereby lacking accuracy since pushing/pulling in industry are seldom static in nature (Todd, 2005).

Although the tasks under investigation are representative of those commonly occurring in industry, they were evaluated under strict laboratory conditions, allowing for standardised procedures and the exclusion of extraneous variables which may affect findings. Essentially, adopting this approach permits a more rigorous control of experimentation, enhancing accuracy of measures by isolating variables of interest, and improving a study's reliability.

PILOT STUDIES

Extensive pre-pilot and pilot investigations were performed in the Department of Human Kinetics and Ergonomics at Rhodes University, primarily to determine if methodological procedures and equipment were appropriate, for clarification of experimental protocols, familiarisation of equipment and to gain a preliminary overview of expected research outcomes.

Selection of Walkway

Pilot tests facilitated appropriate selection of the walkway to be employed during experimentation. It was deemed necessary to choose a surface that not only permitted high shoe/floor friction to prevent slipping but also a low rolling friction between the wheels of the pallet jack and the floor so that moving the pallet jack was not excessively physically taxing. Although wheel selection should be based on flooring (Eastman Kodak, 1986; Das **et al.**, 2002), wheels of the pallet jack were fixed, such that flooring was chosen based on wheels. Drawing on existing literature (Ciriello, 2005), an untreated plywood surface (120mm thick, 2440mm wide) was found to be appropriate for the tasks to be performed, allowing the coefficient of friction to be within the recommended limits of 0.4 to 0.6 (Sotter, 1995). Through pilots, it was concluded that a combination of rubber-soled training shoes worn by subjects and plywood surface provided adequate shoe/floor friction. Pushing/pulling the pallet jack with the given loads along this surface did not elicit excessive strain on the musculoskeletal system during task performance.

In the same way, it was necessary to determine an appropriate distance for task execution. According to Mack **et al.** (1995), distances covered during pushing and pulling of manual vehicles is highly variable in industry. Thus selecting the distance for experimentation was dictated by the need to be able to differentiate between the motion phases (initial, sustained and ending) of pushing/pulling. While satisfying this criterion, distance also had to be short enough that subjects did not become unnecessarily fatigued. As such, a distance of 10m was found to be adequate.

Selection of Load Mass

To make the current research applicable to vocational settings, it was essential that the experimental design represented tasks in industry as closely as possible, yet excluded impinging variables as far as possible. For this reason load masses commonly evidenced in the work setting were employed. Load masses transported on manual vehicles vary considerably in different industrial sectors, ranging from 2kg to 1500kg (Mack **et al.**, 1995). As such selection of load mass was maintained within

this range, and was also based on maintaining the task demands within safe limits, with numerous authors (Lawson **et al.**, 1993; Resnick and Chaffin, 1995; van der Beek **et al.**, 2000) concluding that load mass should be minimised to prevent undue musculoskeletal stress. Loads were not relativised according to individual masses as this was perceived to be unrepresentative of the 'real' milieu.

Selection of Manual Vehicle

Since the purpose of the research was to determine an ideal push/pull technique, it was essential that an appropriate manual vehicle be selected. The hydraulic pallet jack was employed primarily because it is a standard, widely available manual vehicle, and according to Li **et al.** (2008) commonly used in industry. Furthermore, due to the non-experienced make-up of the group of subjects in terms of manual work and particularly pushing/pulling, a manual vehicle that facilitated easy use was required. Pilot studies determined that non-experienced individuals easily learnt how to use it with specific reference to steerability and control. As such the hydraulic pallet jack was found to be suitable. It was 78kg in mass when unloaded and had a swivelling rear wheel 175mm in diameter while the two fixed front wheels were 70mm in diameter. The pallet jack arm was secured in an upright position to minimise the possibility of exerting forces in other directions other than horizontal and the handle height was fixed between radiale and acromiale heights for all individuals at 1175mm, once again being representative of manual vehicles and trolleys in industry where handles are usually not adjustable. Although no one handle height has been found to be appropriate in all situations, a vast proportion of the literature during dynamic efforts points to a handle located at or between the aforementioned anthropometric landmarks (Lee **et al.**, 1991; de Looze **et al.**, 2000; Jansen **et al.**, 2002; Hoozemans **et al.**, 2004; Pheasant and Haslegrave, 2006).

Speed of Pushing and Pulling

To enable comparison of experimental conditions, it was necessary to control the speed at which participants pushed/pulled the pallet jack. During pilot testing different speeds were investigated using a light emitting diode (LED) system and relativised

according to subject stature. Through self reports, a comfortable walking speed, appropriate for the distance to be covered and loads to be transported was identified and set between 0.45 to 0.55 statures.s⁻¹, classified as “slow” (Appendix B) according to Charteris (1982). In essence, at this speed a subject is covering a distance of 45% to 55% of stature in overground distance per second. Use of a relative speed means all subjects were equally physically taxed, preventing speed of movement from becoming a limiting factor (Charteris, 1982). At the end of each trial, speed was recorded to ensure subjects walked at the acceptable pace. If not, another trial was performed until there was consistency between speeds, such that three successful trials were achieved per condition. For the load masses being moved, this was thought to be reasonable in terms of minimising strain experienced while allowing accuracy of results.

Muscle Selection

Preceding experimentation, electrical activity of numerous muscle sites on the torso and upper extremities (Table V) were investigated using surface electromyography (EMG). The purpose was to identify the muscles most active under the three chosen push/pull techniques to select the most appropriate muscle sites for testing (Appendix C). Previous literature (Hoozemans **et al.**, 1998; Hoozemans **et al.**, 2002), identifying the neck, shoulders, upper extremities and lower back as experiencing pain provided an initial reference for muscle selection. Following pilot testing, four muscles, namely the biceps brachii, pectoralis major, external abdominal obliques and rectus abdominis were observed to show minimal activity during all three forms of pushing/pulling and were excluded from final experimentation. The final eight were selected and are highlighted in grey in Table V.

The final muscle selection, based on function and action during pushing/ pulling, were also chosen because they represent major regions of the torso and upper limbs. Importantly, accessibility and proximity to the skin surface also dictated appropriate muscle selection, with Anders **et al.** (2004) arguing that surface EMG does not allow for the assessment of deep muscles, but only those lying directly under the skin's

surface. Although James *et al.* (2004) argued that the biceps brachii were subjectively reported as contributing to static maximal pushing efforts, pilot studies showed muscle activity to be minimal. The contradiction may be a result of the differences between the nature of the activities, with one being static and the other dynamic.

Table V. Muscle selection for final experimentation

<i>Muscle site</i>	<i>Movement</i>
Brachioradialis	Elbow flexor
Biceps brachii	Elbow flexor
Triceps brachii	Elbow extensor
Anterior deltoid	Shoulder flexor
Medial deltoid	Shoulder abductor
Posterior deltoid	Shoulder extensor
Trapezius	Shoulder elevation
Latissimus dorsi	Shoulder adductor
Erector spinae	Trunk extensor
Pectoralis major	Shoulder transverse flexor
External abdominal obliques	Trunk abductor and rotator
Rectus abdominis	Trunk flexor

■ Muscles selected for experimentation

For symmetrical tasks (two-handed pushing and two-handed pulling), muscle activity levels were similar for all muscles on the right and left sides of the body (Appendix C). As expected, for one-handed pulling, muscle activity was greater on the 'driving' side, such that pulling with the right arm elicited higher muscle activity in the muscles on the right side of the body (Appendix C). It was only when the participant was required to bring the pallet jack to a standstill with both hands that muscle activity was approximately equal in both sides. Hence during experimentation EMG electrodes were only placed on the right side, as the left side was either equally active or not active at all depending on the technique adopted.

During pilots, it was also established that subjects would be required to attend one habituation session and one testing session, lasting approximately 90 minutes each. According to Lippold (1952) intra-subject reliability is improved when electrodes are

not replaced, implying that testing must be completed in a single session. Therefore it was essential that electrodes be positioned identically under all conditions and during maximal voluntary contractions (MVCs), allowing responses to be expressed as a percentage of MVC. Although the effects of muscle fatigue were acknowledged it was concluded that the non-continuous nature of the tasks (only three successful trials were warranted per condition) and the load masses under consideration, would mean that muscles would not necessarily become fatigued. It was ascertained that each trial, completed in approximately 12s, with a total of 216s of work being performed per testing session, was unlikely to cause excessive muscle fatigue. Additionally, rest periods of up to five minutes were allotted prior to testing a new condition, thereby reducing the likelihood of fatigue.

EXPERIMENTAL DESIGN

The objectives of this study were to compare hand force production, spinal kinematic variables, electric activity of the upper body muscles and perceptual ratings of body discomfort while performing three commonly adopted push/pull techniques using two different loads. These techniques were two-handed forward pushing, two-handed backward pulling and one-handed forward pulling. Backward pushing and one-handed pushing or a combination of the two are not often witnessed in industry and were therefore not considered paramount to this investigation.

Table VI. Design matrix of experimental conditions

		<i>Technique</i>		
		<i>Two-handed forward pushing</i>	<i>Two-handed backward pulling</i>	<i>One-handed forward pulling</i>
Load (kg)	250	1	3	5
	500	2	4	6

Where 1, 2...6 represent the six experimental conditions

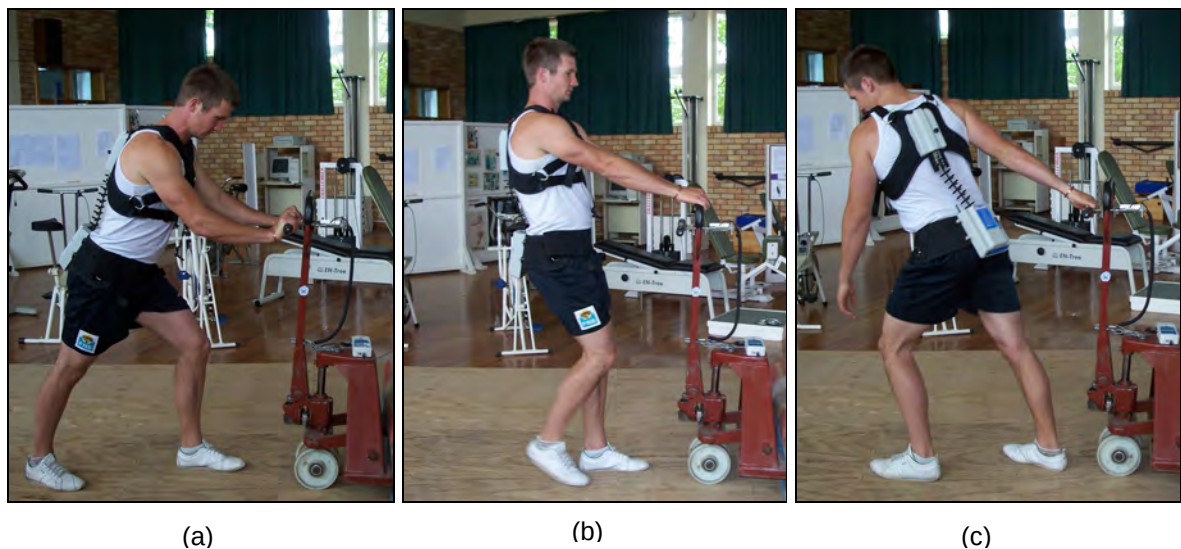


Figure 7. Three dynamic push/pull techniques under investigation

Consequently, six conditions, shown in the design matrix (Table VI) were performed to determine if significant differences existed between the three techniques for the same load, providing valuable information pertaining to the strain experienced by subjects during experimentation. Further, experimentation allowed for an assessment of the impact of load on responses to push/pull tasks. Experimentation involved two-handed forward pushing (Figure 7a), two-handed backward pulling (Figure 7b) and one-handed forward pulling (Figure 7c), of a pallet jack over a distance of 10m along a plywood walkway with a 250kg or 500kg load. Within each condition, three successful trials were warranted, such that speed of walking was between 0.45 and $0.55 \text{ statures.s}^{-1}$ and effort levels of force output were similar, ensuring intra-subject consistency. Where trials were unsuccessful, additional pushes or pulls were performed.

INSTRUMENTATION

Anthropometric and Demographic Variables

To prevent certain anthropometric and demographic characteristics from affecting measured variables, individuals were required to fulfil specific criteria related to age,

stature, mass, radiale and acromiale heights and hand dominance, all of which were recorded. An individual not meeting all requirements was excluded from the sample group.

Stature: Harpenden Stadiometer

Stature, measured vertically from the soles of the feet to the apex of the head in the mid-sagittal plane, known to influence hand forces (van der Beek **et al.**, 2000) and therefore spinal loading (Jansen **et al.**, 2002), was delimited to a range of 1700mm to 1900mm. A portable Harpenden Stadiometer was employed to gauge stature to the nearest millimetre. Wearing no shoes, subjects stood upright with arms pendant, heels, buttocks, upper back and posterior of the head rested against the vertical stand of the stadiometer and feet together. With the head directed in the Frankfurt-horizontal plane, the sliding portion of the stadiometer was adjusted until it was in contact with the vertex of the head and stature recorded.

Body mass: Toledo Scale

Body mass is known to impact the force that an individual can exert, such that the higher the mass, the greater the force achieved (Kroemer, 1969; Ayoub and McDaniel, 1974; Chaffin **et al.**, 1983). It was postulated that since the load mass of the pallet jack to be overcome would be the same for each subject, it was not necessary to control mass. However, in attaining the same forces, individuals with higher body masses (specifically lean body mass) more easily achieve them compared to those with lower masses, and hence are less likely to over exert themselves. Therefore, mass was recorded to express force exertion relative to body mass, providing an estimation of strain placed on the musculoskeletal systems of the subjects.

Mass was measured using an electronic Toledo Scale to the nearest 0.01kg. Wearing minimal clothing and no shoes, subjects stood upright in the centre of the scale with body mass distributed evenly between the feet and head directed in the Frankfurt-horizontal plane. Mass was recorded with the individual in static equilibrium.

Acromiale and radiale heights: Anthropometer

As handle height influences the posture adopted (Ayoub and McDaniel, 1974), hand forces produced (Daams, 1993) which in turn affect the forces experienced in the spine, it was crucial that handle height was similar for all participants. In this way, radiale and acromiale heights provided anthropometric landmarks between which handle height was situated. Using a functional anthropometer, these vertical distances were recorded to the nearest millimetre. All measurements were taken on the right side of the body, with subjects adopting a comfortable upright posture, arms pendant, barefoot and head directed in the Frankfurt-horizontal plane.

To measure acromiale height, the vertical distance from the floor to the acromion process, the spine of the scapula was palpated laterally until the anthropometric landmark was located. For radiale height, with palms facing medially, the elbow was palpated until the proximal end of the radius was found and the vertical distance from this landmark to the floor was recorded.

Biomechanical and Perceptual Variables

Hand forces: Chatillon® DFS Digital Force Gauge

To measure forces exerted at the hands, with an accuracy of 0.1% full scale, during each motion phase of pushing/pulling, the Chatillon® DFS Digital Force Gauge (AMETEK Inc., 2005) was employed. Since stature was delimited, ensuring an optimal handle height and promoting forces primarily in the horizontal plane, a uniaxial force gauge was adopted. Using an adaptor handle (Figure 8), the handle of the pallet jack was connected to the Chatillon, which in turn using electric cabling was linked to a laptop computer loaded with the corresponding Nexygen DF Series Software package. This software program facilitated recording and observation of force output graphically and numerically. The laptop was placed on the pallet jack, with its mass being included in the overall load to be moved under each condition. To ensure forces were primarily horizontal, the force gauge was calibrated and checked for lateral and vertical cross talk after being mounted to the pallet jack.

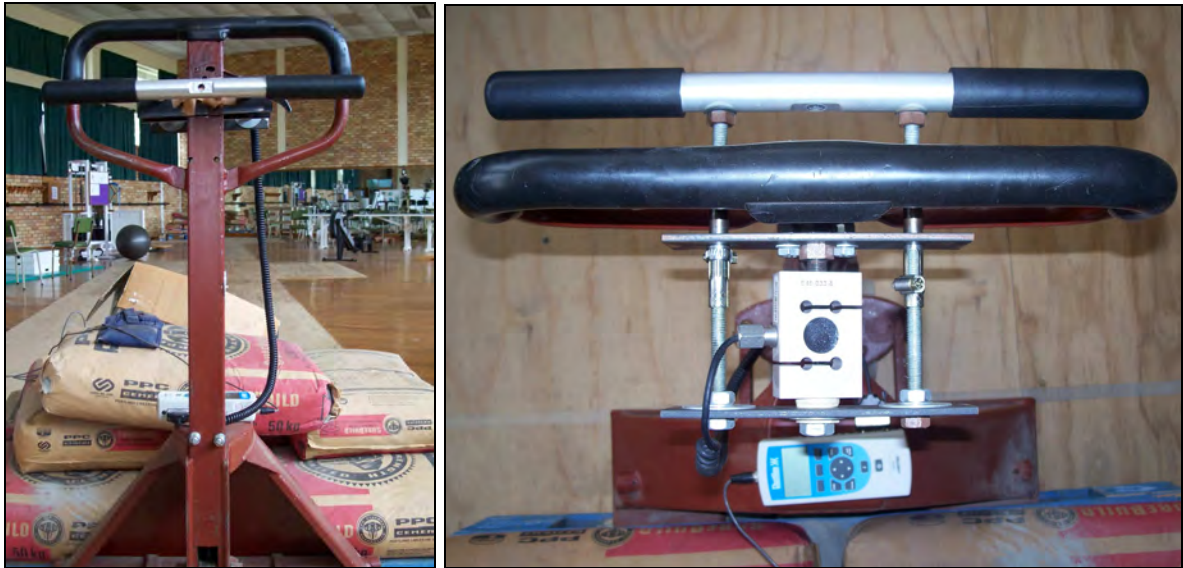


Figure 8. Handle of pallet jack and Chatillon adaptor handle

The Chatillon, capable of measuring compressive and tensile forces (in Newtons) in real-time, sampled at a rate of 5000Hz and provided data pertaining to raw, peak and average forces. A graphical tracing of force output against time was displayed on the laptop screen. Together, these were used to assess whether or not there was consistency between trials per condition, which determined if a trial was successful. The raw data, together with time elapsed were saved and then exported to Microsoft Excel for further analysis. This allowed for differentiation and analysis of the initial, sustained and ending forces. Recording of force data occurred for the duration of each successful trial.

Spinal kinematics: Industrial Lumbar Motion Monitor™

Previously, most tools used to investigate the risk of lower back disorders made the unrealistic assumption that motion does not have a key role to play in their proliferation (Marras and Allread, 2005). However the converse is true (Allread **et al.**, 2000). To address this gap, the Industrial Lumbar Motion Monitor (iLMM) (BioDynamic Solutions, Inc., 2002), a triaxial electrogoniometer was designed. It is used to measure the instantaneous three-dimensional position of the working spine relative to the pelvis when manual tasks are performed, following which velocity and

acceleration in all three planes can be derived (Marras **et al.**, 1992; Marras and Allread, 2005).

Designed to replicate spinal movement, it is essentially a lightweight exoskeleton of the human lumbar spine. It is fixed via a harness system at the level of the pelvis and chest on the human back in parallel to the anatomical spine where it moves synchronously to spinal motion (Marras **et al.**, 1992). T-sections of the iLMM, mimicking T-sections in the posterior of the human vertebrae, guide the iLMM and are connected to three potentiometers in the base of the unit via wires. Movement in the sagittal and frontal planes causes the wires to differentially change the voltage in the potentiometers. A fourth potentiometer, connected by a thin flexible rod placed through the junction of each T-section reacts to movement in the transverse plane. The voltage readings are then transmitted at a frequency of 60Hz (Ferguson and Marras, 2004) to an analog-to-digital convertor and subsequently recorded on a computer, where data is made into meaningful information related to position, velocity and acceleration of the spine in all three cardinal planes. For this study, data from the iLMM were transmitted to the computer via telemetry due to the distances moved by participants. The software used to facilitate use of the iLMM was the BALLET 2.0 Software package. Following completion of a trial, the data were saved, and later exported to Microsoft Excel for further analysis.

Marras **et al.** (1992) assessed the accuracy and reliability of this instrument to measure the purported variables related to spinal kinematics by comparing it to a two-dimensional video-based motion analysis (MA) system. Overall the authors concluded that the iLMM is highly accurate and allows for repeatability of results, with the relative position error being half that of the MA system and prediction of velocities and accelerations being similar. More recently, Gill and Callaghan (1996) reported that the variability of repeated measures with the iLMM is low for range of motion and velocity, indicating high reproducibility. Furthermore they concluded that it is suitable for application in clinical and research environments.



Figure 9. Placement of lumbar motion monitor on participant's back

Prior to testing and while still in its storage case, the iLMM was zero-calibrated and prepared for placement on the subject. The iLMM was secured to the participant via a harness system at the shoulders, around the thorax and at the level of the pelvis (shown in Figure 9). Once securely fastened in parallel to the participant's spine and with the inferior edge of the top harness in line with the scapulas' inferior angles and the superior edge of the bottom harness in line with the sacroiliac notches, the second calibration was performed for the individual. This calibration allowed all subsequent spinal motions to be measured relative to the individual's pelvic position and natural spinal curvature. It required that the participant stand stationary with feet together, hips, knees and ankles facing forward and head directed in the Frankfurt-horizontal plane. During experimentation, spinal kinematic data were recorded for the duration of each trial, for three successful trials per condition.

Muscle activity: Megawin ME6000 Muscle Tester

The principle underlying electromyography (EMG) is that electric signals are generated during muscular contractions, permitting investigation of muscle function (Kumar, 1996; Göbel, 2005). The Muscle Tester “Mega ME6000” (Mega Electronics Ltd., Finland) unit was used to measure the electric activity (measured in μV) of eight muscles on the trunk and upper limbs during experimentation. These signals are picked up by disposable pre-gelled silver chloride electrodes placed on the surface of the skin directly above the muscles of interest and are transmitted to the EMG unit. The unit comprises four EMG pre-amplifier cables, each allowing four muscles to be tested at a time. The current investigation made use of only two channels, sampling at a rate 1000Hz. These channels connect the electrodes on the skin to the EMG unit and during muscular work, transmit the signal picked up between the active electrodes to the EMG unit for pre-amplification, permitting further processing (Göbel, 2005). Using telemetry, the data were transmitted to a laptop, loaded with the Megawin2.4 software, allowing for real-time graphic monitoring. The electric activity was measured continuously during testing, with markers set at the beginning and end of each trial. On completion of testing, data were saved and later converted to ASCII format, following which they were analysed using a software analysis tool.

According to Göbel (2005), there has been minimal research into the reliability of EMG. He argued that inter-subject reliability of direct measures is low, largely due to the individual differences in muscle geometry, subcutaneous tissue and electrode placement. To compare between subjects, a normalization process must be carried out, whereby muscle activity is expressed as a percentage of MVC (Soderberg, 1992; Göbel, 2005). Similarly, comparisons between muscles must be excluded because of the differences in constituencies of body tissues (Soderberg, 1992; Göbel, 2005). On the other hand, intra-subject reliability can be augmented if electrodes are not replaced, with reliability coefficients of up to 0.99 (Lippold, 1952). Overall, reliability of EMG can be improved through the practice of certain procedures during the set-up process, such as careful preparation of the skin surface and placement of electrodes (Soderberg, 1992).

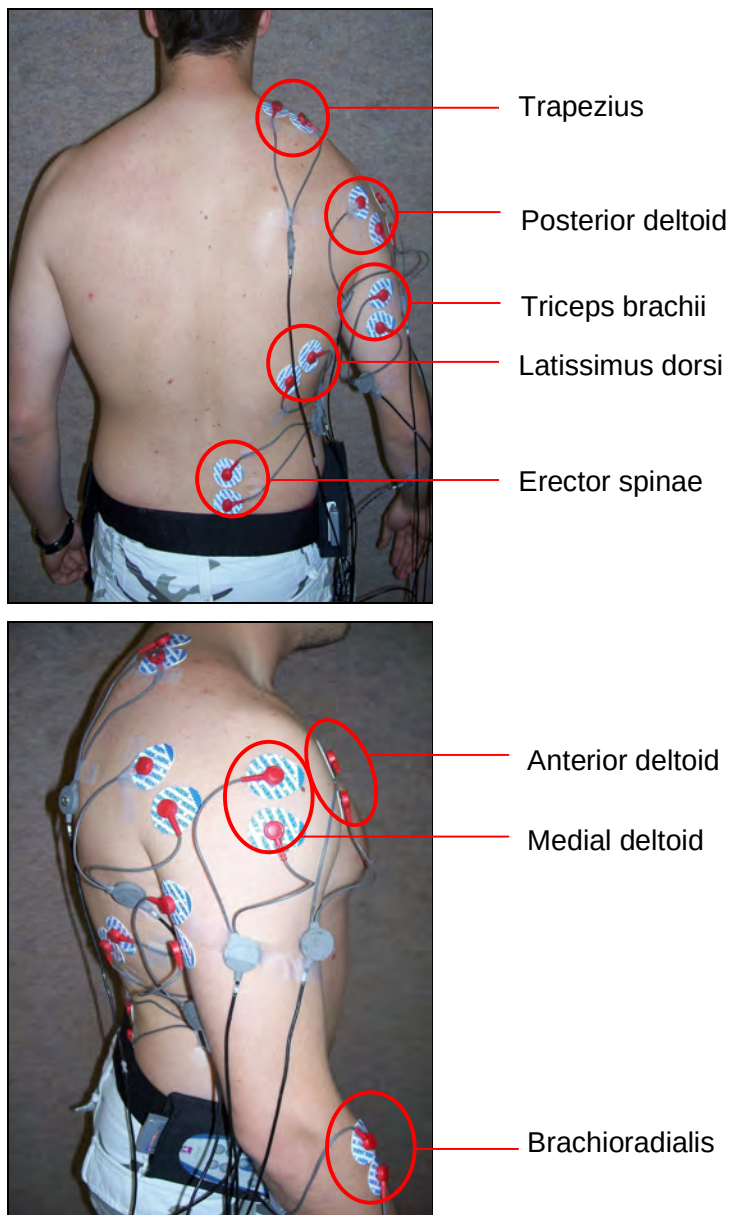


Figure 10. Electrode placement for the eight muscles under investigation

Subject preparation included shaving hair off skin areas where the surface electrodes were to be placed and cleaning the skin surface with an alcohol swab to augment conductivity. Electrodes (35mm diameter) were placed in a bipolar configuration on the muscle belly (shown in Figure 10), with a spacing of approximately 20mm between them, and a neutral third was placed away from the active muscle for grounding. All were located on the right side of the body. Once electrode placement

was completed correctly, MVCs were performed for all muscles tested as shown in Appendix B (Kendall **et al.**, 1993) to normalise muscle activity during testing to an individual standard. In this way responses acquired during testing could be expressed as a percentage of the MVC. Each contraction was held for 3s, a process which was repeated twice. During experimentation, muscle activity was recorded continuously, with markers set at the beginning and end of each trial.

Digital camera

A Kodak EasyShare C875 Zoom Digital Camera was used during testing to take photographs while subjects initiated movement of the pallet jack during each experimental condition. This phase, considered to be the most challenging in terms of overcoming inertial and wheel/floor frictional properties of the load, can be approximated to a static task. The camera was set up in a demarcated area on a table, perpendicular to the plane of motion to ensure consistency of angle at which photographs were taken. One photograph per condition, deemed to be representative of the general postures assumed was later uploaded into a software package ErgoImagerTM (NexGen Ergonomics, Inc.), which interfaces with the Three Dimensional Static Strength Prediction ProgramTM (3DSSPP) developed at the University of Michigan. Using this program, estimates of spinal compression and shear forces were obtained, indicating the risk associated with the tasks.

Perceptual discomfort: Body Discomfort Scale

The perceptual demands of the tasks were inferred using the body discomfort scale (Appendix B), originally conceptualised by Corlett and Bishop (1976) to indicate where muscular discomfort was experienced and the extent of this while performing work. The principle underlying its application is that awkward working postures elicit pain. Areas experiencing pain can then be identified using body discomfort maps. The scale is made up of two body maps, representing the anterior and posterior parts of the body, each of which is segmented into 28 numerically labelled parts. On completion of one condition, the maps were presented to the participant who selected the area(s) in which discomfort was subjectively perceived and indicated the

corresponding degree of discomfort on a Likert-type rating scale, with 1 representing 'very slight discomfort' and 10 'very uncomfortable.'

SUBJECT CHARACTERISTICS

Subjects participating in the study were drawn from a student population at Rhodes University, representing different ethnic groups. 36 healthy males were recruited, all satisfying anthropometric criteria known to affect the measured responses, presented in Table VII. The sample group was aged between 19 and 28 years, with a mean stature and mass of 1796 (± 44)mm and 78.41 (± 10.14)kg respectively. Mean acromiale and radiale heights were measured as 1454 (± 47)mm and 1123 (± 39)mm respectively.

Table VII. Descriptive characteristics of participants (n=36)

	<i>Age</i>	<i>Stature (mm)</i>	<i>Mass (kg)</i>	<i>Acromiale height (mm)</i>	<i>Radiale height (mm)</i>
Mean	21.69	1796.28	78.41	1454.22	1122.81
SD	2.45	44.46	10.14	47.26	38.68
CV (%)	11.30	2.48	12.93	3.25	3.44

where SD = standard deviation

CV = coefficient of variation expressed as a percentage

Although no formal medical examination was conducted, self-reports established that all subjects were free of illness, musculoskeletal injuries and had no previous injury history, specifically involving the back and upper extremities.

ETHICAL CONSIDERATIONS

Before testing commenced, the study was approved by the Rhodes University Research Ethics Committee. Pilot investigations were carried out to ensure that potential problems were addressed before testing to minimise the risk of injury. During habituation, all subjects were fully informed of the nature of the investigation and were questioned regarding their health and injury history, after which they gave oral and written consent (Appendix A). Subjects found to be injured or suffering from

previous injuries were excluded from the investigation. All subjects were informed that they were free to exclude themselves from participating should they choose to. During experimentation, subjects were frequently questioned as to their well-being and were encouraged to inform the researcher should they feel ill or in pain.

EXPERIMENTAL PROCEDURES

Participants attended two sessions in the Department of Human Kinetics and Ergonomics at Rhodes University, the first for habituation and familiarisation and the second for experimentation, each lasting approximately 90 minutes. Small groups of four or five subjects attended habituation at any one time. During this session subjects were provided with letters of information (see Appendix A) related to the study, following which a more detailed verbal description of the objectives and experimental framework was provided. They were introduced to the equipment, given a detailed description regarding equipment use and application and shown how equipment was to be worn. Similarly, detailed verbal explanations for the use of the body discomfort scale were provided together with written instructions and a picture of the scale (Appendix B) for subjects to become familiar with. Individuals were informed of various guidelines to adhere to prior to testing (Appendix B) for standardisation purposes and to exclude as much as possible the interference of impinging factors. They were instructed to wear a loose vest or t-shirt for minimal interference with the electrodes and rubber-soled athletic training shoes to allow for an adequate coefficient of friction between the shoe/floor interface to avoid slipping. If a subject was found to contravene any stipulations, testing was rescheduled. Once fully conversant, informed consent was received from all participants.

Anthropometric and demographic information, including age, stature, mass, acromiale and radiale heights and hand dominance were recorded. At this stage, only subjects who were right-hand dominant were selected for standardisation purposes. Next, participants were afforded the opportunity to familiarise themselves with pushing/pulling of the pallet jack for all three techniques under investigation and the appropriate walking speed until both subject and researcher were confident that the

task could be performed adequately. Particular emphasis was placed on the protocol to initiate and stop movement of the pallet jack, including avoiding 'jerky' or sudden movements because technique influences the forces produced (Bennett **et al.**, 2008). On starting, for standardisation purposes, the feet were staggered with the right behind the left for all conditions. Due to right handedness of all subjects, it was conceived that under the given conditions it would be appropriate for the right foot to be positioned behind because it was the 'push off' or 'driving' foot. On ending, a line demarcated at 8.5m of the walkway indicated when subjects should start slowing the trolley down to easily differentiate between the sustained and ending phases of motion. On reaching the 10m line, subjects were required to bring the pallet jack to a complete standstill. Having completed habituation, participants were asked to select suitable days for experimentation, with the only stipulation being that they must not have performed heavy physical work or exercise two days prior to testing to prevent delayed onset muscle soreness from affecting muscle responses and their ratings on the body discomfort scale.

For experimentation, each participant was required to attend one session of testing for all six experimental conditions in a laboratory setting at the Department of Human Kinetics and Ergonomics at Rhodes University. The order in which the conditions were performed was randomised to prevent any order effects (Appendix B). To minimise muscle fatigue, the subject was never required to perform three consecutive experimental conditions with the highest load of 500kg.

Prior to subject arrival, all equipment was checked to ensure that all were in proper working order and ready for testing and the appropriate load was selected. On arrival the researcher reminded the subject of the appropriate technique to initiate and end movement and the use of the body discomfort scale. All subjects were also reminded that should they wish to do so, they could terminate participation in the study at any time.

Electrodes were placed on the appropriate muscle sites (see Figure 10, page 62), after which MVCs were performed. Following this, the subject was allotted time to recover and the iLMM was fitted on to the back and individually calibrated. Pilot investigations, with and without the subject wearing the iLMM previously demonstrated that the iLMM did not interfere with the EMG electrodes and the associated responses. Once the preparation was completed, the Chatillon was zeroed without the subject exerting any force and the participant was informed of the testing condition to be performed.

Depending on the condition to be completed, the subject pushed or pulled a commercially available hydraulic pallet jack over a measured distance of 10m along a plywood walkway, with either a load mass of 250kg or 500kg. At the end of each trial, the speed was recorded to ensure it fell within the required range. The participant was not required to turn the manual vehicle at the end of the marked 10m distance; instead the researcher performed this task while the subject rested between trials. Three trials were performed for each condition, after which the subject was afforded the opportunity to rest before beginning another condition. The work-rest ratio was approximately 1:3, such that for every minute of work, there were at least three minutes of rest. This is deemed to be adequate given that literature suggests that the ratio should not be higher than 3:1 (van Dieën and Oude Vrielink, 1998).

The external load moment (distance from body's centre of mass to handle interface) was measured on initiating trolley motion and bringing the trolley to a stop, using a tape measure. Although a crude measurement, pilot testing indicated that if measured meticulously there was little intra- and inter-subject variability within each condition. This measurement would later be inputted to the BALLET 2.0 Software package, to be used, together with other factors, to determine the risk of lower back disorders associated with each condition. Hand force output, trunk motion characteristics and EMG were measured and recorded for three successful trials. Photographs were taken once for each condition, on initiating movement of the manual vehicle. Body discomfort was recorded on completion of each condition, with the subject being

required to provide the appropriate body site(s) and associated numerical rating. On completion of testing subjects were thanked and permitted to ask questions regarding their performance.

STATISTICAL TREATMENTS

All data were analysed using the STATISTICA 8 (Statsoft Inc., 2008) software programme. Descriptive statistics (mean, standard deviation, coefficient of variation) were calculated, followed by two-way analysis of variance (ANOVA) for all variables to assess significant effects, and lastly post-hoc analyses (Tukey pair-wise comparisons). These allowed for identification of differences between techniques at the same loads and vice versa. Additionally one-way ANOVAs were performed, determining if significant differences existed between the motion phases of pushing/pulling for hand force exertion for each condition. EMG data were specifically transformed for normality using the natural log function, and all subsequent analyses were performed on these (although all values within results are shown as a percentage of MVC). The significance level was set at 95%, allowing for 5% chance of making a Type I error (rejecting a true hypothesis).

CHAPTER IV

RESULTS

HAND FORCE EXERTION

Hand forces produced to move an object during pushing/pulling are considered indicative of the degree of stress imparted on a worker while performing MMH activities (Hoozemans **et al.**, 1998; van der Beek **et al.**, 1999), and are therefore of concern when recommending safety limits to industry. Dynamic pushing/pulling can be distinguished into three motion phases, namely the initial, sustained and ending phases, each of which is characterised by a unique force output pattern. Figure 11 outlines typical tracings of force output for two-handed forward pushing and two-handed backward pulling (note that one-handed forward pulling follows a similar pattern) of 250kg, taken from the current study.

Horizontal force output for pushing and pulling occurs in different directions. For example during the initial phase, where forces are positive for pushing, they are negative for pulling. Force direction alters when bringing the pallet jack to a standstill, such that for pushing the ending forces are negative compared to the positive forces produced during the initial and sustained phases of motion (and vice versa for pulling). To ensure a realistic analysis of hand forces in the present investigation, all statistical analyses were performed on absolute values.

The initial and ending phases are characterised by distinct peaks in force output to overcome the inertia of the vehicle when initiating and stopping movement, and for this reason, these phases are often considered paramount in predicting the risk of overexertion (Drury **et al.**, 1975; Mack **et al.**, 1995; van der Beek **et al.**, 2000; Laursen and Schibye, 2002; Hoozemans **et al.**, 2004; Jung **et al.**, 2005). It is equally critical to acknowledge that the initial and ending phases occur over short durations when compared to the sustained phase, perhaps suggesting that consideration of sustained forces is necessary because exerting a force, even if submaximal, for a substantial period, may contribute to static muscular and joint loading, leading to fatigue and cumulative trauma. This study was thus concerned with forces generated in all motion phases.

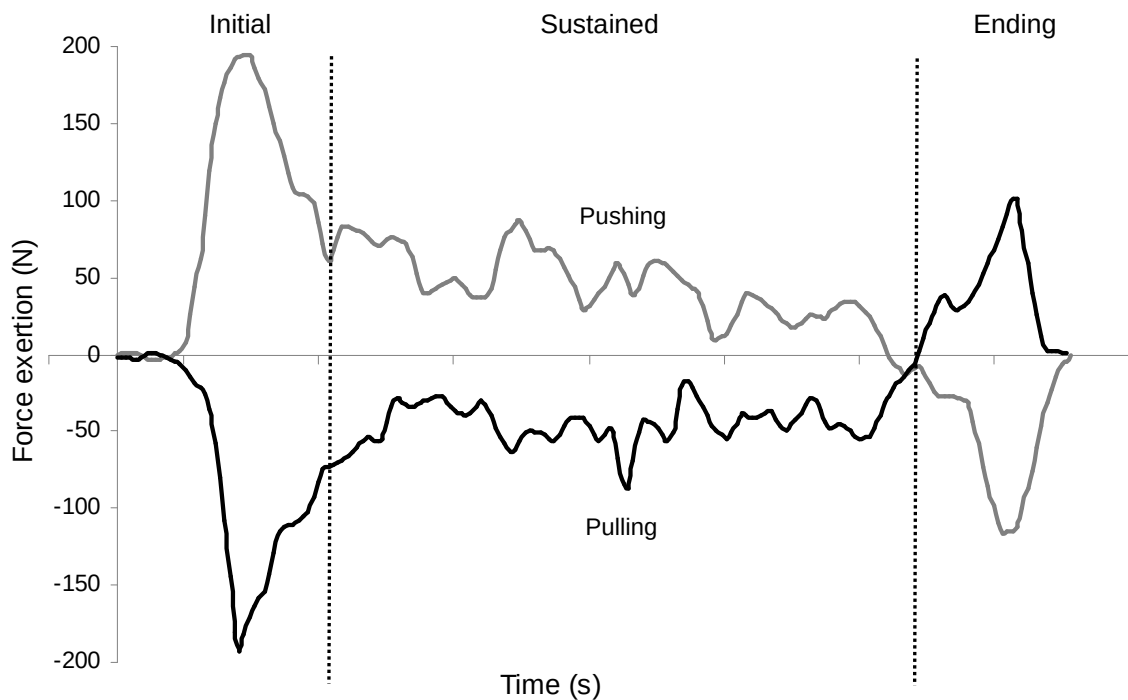


Figure 11. Typical tracings of force output for pushing and pulling, with motion phases indicated

Initial Forces

Impact of technique

Although there was no interaction between technique and load mass, each independently affected the mean peak hand forces exerted during the initial phase. The impact of technique was statistically significant, with pushing responses being 29N (aggregated for both loads) higher than those of one-handed pulling, but both being statistically similar to two-handed pulling. Referring to Table VIII, at each load, forces were highest while pushing and lowest during one-handed pulling. At the lower load, no statistical differences were apparent, with all three techniques being statistically similar and exhibiting an average force of 188N. At 500kg however, pushing ($327 \pm 35\text{N}$) was significantly higher by 11% than one-handed pulling ($294 \pm 24\text{N}$), but both techniques were comparable to two-handed pulling. This may be in part explained by the position of the load relative to the individual. During pushing, the position of the load means that its inertia must be overcome before movement occurs, whereby the individual must first exert effort. Contrastingly, during both one- and two-handed pulling, the individual is

able to take a step in the intended direction of motion before the pallet jack moves, employing momentum to initiate movement thereby evidencing lower hand forces.

Table VIII. Impact of technique on mean peak initial hand forces (N) for each load

<i>Load (kg)</i>		<i>Push</i>	<i>2-handed pull</i>	<i>1-handed pull</i>
250	Mean	198.36	191.78	173.44
	SD	19.59	18.22	14.28
500	Mean	327.23	303.17	294.22
	SD	35.19	27.85	24.99

└──┘ Denotes statistical difference ($p < 0.05$)
SD=standard deviation

Within conditions, there was low inter-individual variability in force outputs, reflected in the low standard deviations (coefficient of variation below 11% for each condition). This suggests that individuals were able to exert similar levels of force output for the initial phase within each condition. This finding is warranted based on the fact that the inertia to be overcome did not change within each condition. It must however be acknowledged that some individuals may have over-anticipated the mass of the manual vehicle, and over-compensated by generating forces that were higher than necessary, while others applied a more gradual pressure. This is in accordance with Al-Eisawi *et al.* (1999a) who argued that hand forces produced to initiate movement of a cart were above the necessary minimum, which is a likely outcome if the task demands are submaximal.

Impact of load

Regardless of the technique employed, load significantly impacted hand forces, with those produced at 500kg being on average 120N higher than those at 250kg. Although the forces exerted in the initial phase were highest for pushing at both loads, the greatest increase in forces from 250kg to 500kg occurred during one-handed pulling, resulting in a 70% increase in initial hand forces (Figure 12). For pushing and two-handed pulling, the differences were smaller, at 65% and 58% respectively. These results indicate that load moved is a key determinant of the initial hand forces required to initiate movement during pushing and pulling tasks regardless of technique.

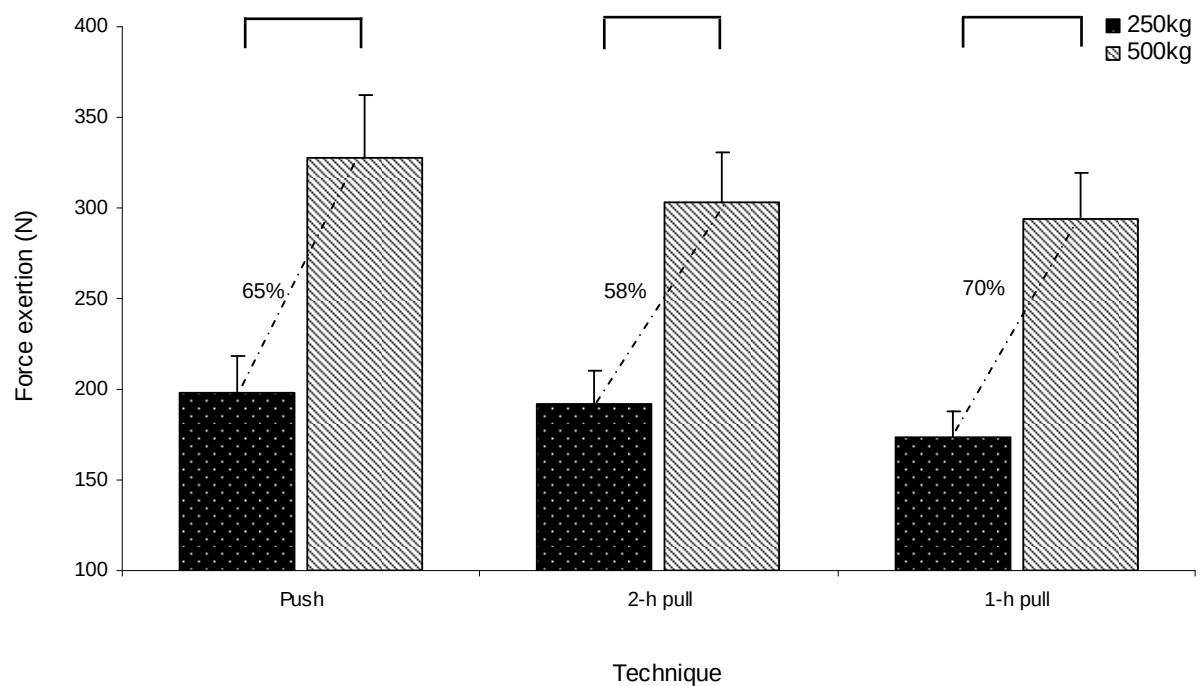


Figure 12. Impact of load on mean peak initial hand forces for all techniques

┌─┐ Denotes statistical difference ($p < 0.05$)

Sustained Forces

Impact of technique

Like the forces produced on initiating movement, technique and load significantly affected the hand forces produced, albeit independently. The overall effect of technique on mean sustained hand forces was statistically significant. Pushing resulted in higher sustained forces (mean for both loads 79N) than either one- or two-handed pulling, which were statistically similar (on average 72N for both loads). At 250kg, there were no significant differences between techniques (Table IX), implying that no one technique is preferable. Conversely, at 500kg pushing responses (111 ± 11 N) were significantly higher (8%) than those of two-handed pulling (103 ± 9 N).

Table IX. Impact of technique on mean sustained hand forces (N) for each load

Load (kg)		Push	2-handed pull	1-handed pull
250	Mean	46.45	42.69	40.80
	SD	5.72	5.22	4.73
500	Mean	111.28	102.80	103.43
	SD	10.72	8.62	8.96

└─┘ Denotes statistical difference (p<0.05)
SD=standard deviation

Low variability in force output (coefficient of variation below 13% for each condition) was apparent within each condition, suggesting that the manner in which participants maintained motion was similar. During this phase, the pallet jack is already in motion, and simply requires individuals to control the movement and use momentum to keep it in moving.

Impact of load

Once again, independent of technique, load had a significant effect on hand forces, with those exhibited at 500kg (mean of all three techniques 106N) being significantly higher than those at 250kg (mean of all three techniques 43N). For each technique (Figure 13), moving the heavier load resulted in statistically higher responses, with forces being increased by more than 140% in each case. The greatest impact was on one-handed pulling where a 154% increase was observed when the load was doubled. For both bilateral techniques, the difference was at least 13% lower.

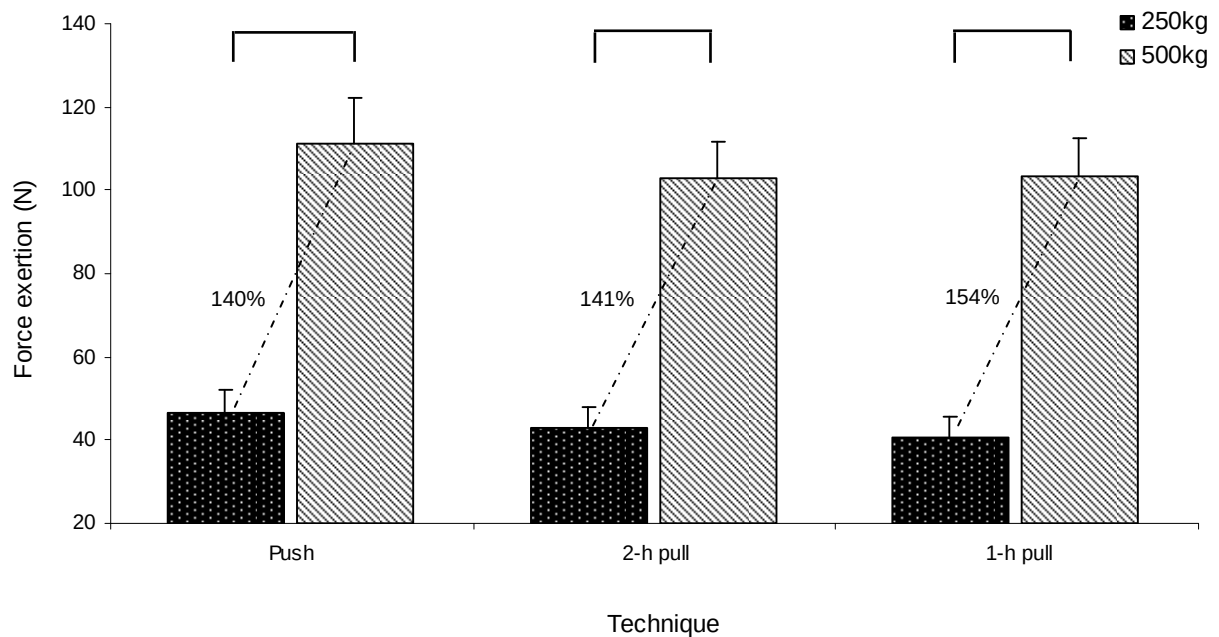


Figure 13. Impact of load on mean sustained hand forces for all techniques

┌┐ Denotes statistical difference ($p < 0.05$)

On average, a substantially smaller increase of 64% was observed for the initial forces. This elucidates that the relationship between load and hand forces changes between motion phases and that although the initial forces are often cited as the most crucial in predicting risk (Drury **et al.**, 1975; Mack **et al.**, 1995; van der Beek **et al.**, 2000; Laursen and Schibye, 2002; Hoozemans **et al.**, 2004; Jung **et al.**, 2005), consideration of load may also be pertinent during sustained exertions.

Ending Forces

Impact of technique

Unlike the forces produced during the initial and sustained phases, technique had no impact on those produced during the ending phase, with the average force being -136N for all six experimental conditions. Whereas pushing forces were highest during the initial and sustained motion phases, one-handed pulling was associated with the highest force output when terminating movement (Table X). Although there was large variation between the highest (178N) and lowest (99N) responses, the high standard deviations (average coefficient of variation 22%) associated with this phase are likely to contribute to the lack of significant

differences found, suggesting that further research into the ending phase is necessary.

Table X. Impact of technique on mean peak ending hand forces (N) for each load

<i>Load (kg)</i>		<i>Push</i>	<i>2-handed pull</i>	<i>1-handed pull</i>
250	Mean	-103.97	-98.63	-113.32
	SD	25.55	20.00	22.76
500	Mean	-159.54	-160.86	-178.31
	SD	36.07	33.41	42.00

□ Denotes statistical difference (p<0.05)
SD=standard deviation

The higher variability in the ending phase compared to those of the other motion phases (where the coefficients of variation were below 13% for each condition) suggests that the manner in which individuals decelerated and stopped movement of the pallet jack was not consistent within each condition. Observation demonstrated that in bringing the pallet jack to a standstill within the 1.5m demarcated area, some individuals tended to decelerate quickly and allow it to roll to a standstill, while others applied a more consistent force. This occurred despite participants being instructed to bring the vehicle to a gradual stop in the habituation and experimentation sessions. Based on this, and in accordance with Bennett **et al.** (2008), the manner in which the manual vehicle was brought to a stop influenced the ending hand forces, implying that there is a need to educate workers as how best to control and stop manual vehicle movement; an area requiring further research.

Impact of load

Similar to initial and sustained forces, load had a significant effect on hand forces in the ending phase, with the higher load of 500kg being accompanied by higher forces (mean for all three techniques -166N) than the lower one (mean for all three techniques -105N). For each technique, forces at 500kg were all significantly higher than those at 250kg, reiterating the role that load mass plays in determining hand forces (Figure 14).

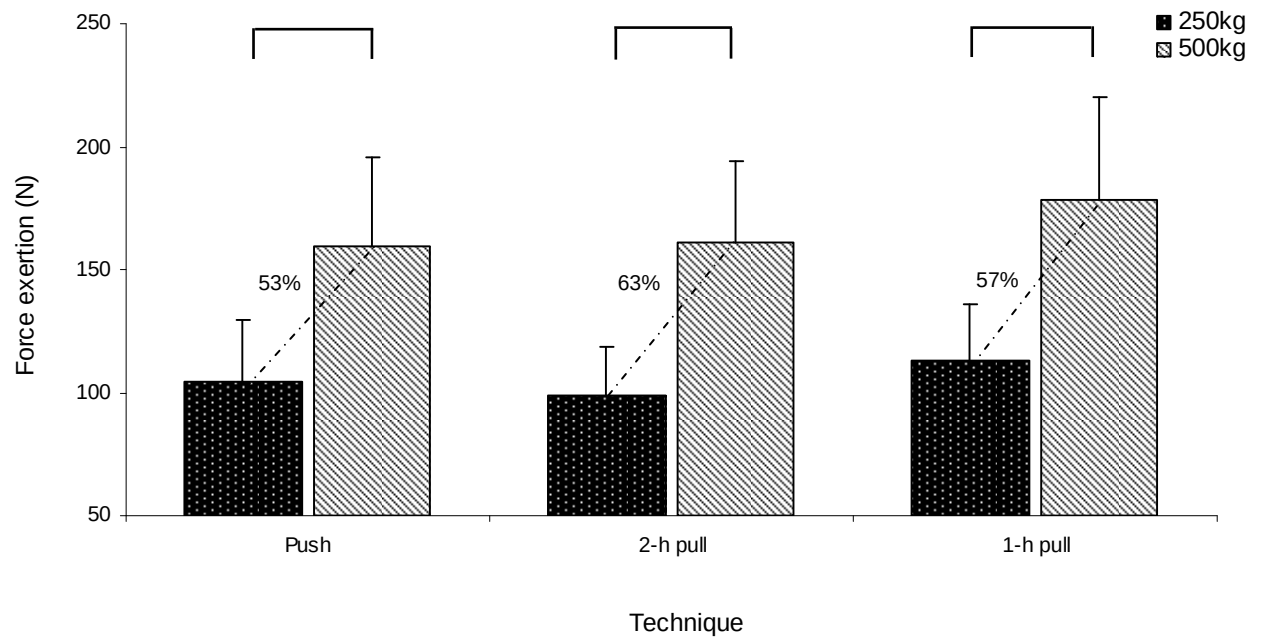


Figure 14. Impact of load on mean peak ending hand forces for all conditions

Denotes statistical difference ($p < 0.05$)

In doubling the load mass from 250kg to 500kg the largest increase of 63% in hand forces occurred for two-handed pulling, while pushing and one-handed pulling resulted in forces increasing by 53% and 57% respectively. This is in contradiction to the initial and sustained forces, where one-handed pulling was associated with the greatest increase. Similar to the differences that occurred on initiating movement of the pallet jack, those of the ending phase were much lower than the differences occurring during the sustained phase, emphasising that load mass is particularly important to acknowledge when maintaining motion of a manual vehicle.

Comparison of Initial, Sustained and Ending Forces

Since the degree of risk of injury is frequently determined by the magnitude of peak initial forces (Drury *et al.*, 1975; Mack *et al.*, 1995; van der Beek *et al.*, 2000; Laursen and Schibye, 2002; Hoozemans *et al.*, 2004; Jung *et al.*, 2005) and sometimes those of the ending phase (Ferreira *et al.*, 2004), it was necessary to identify whether or not forces elicited in all motion phases within each condition were statistically different (see Figure 15).

When comparing the same techniques at the same loads, it was seen that forces produced in the initial phase were statistically higher than those of the sustained or ending phases and moreover, those of the ending phase were significantly higher than those of the sustained phase for all conditions. The largest differences were apparent between the initial and sustained forces. On average, initial hand forces were 334% and 191% higher than the sustained forces at 250kg and 500kg respectively, while ending forces were on average 143% and 57% greater than sustained forces at 250kg and 500kg respectively. Therefore, as load mass increases, the differences between the sustained forces and initial and ending forces are reduced significantly. These findings suggest that as load increases so sustained forces play an increasingly important role in the risk of injury.

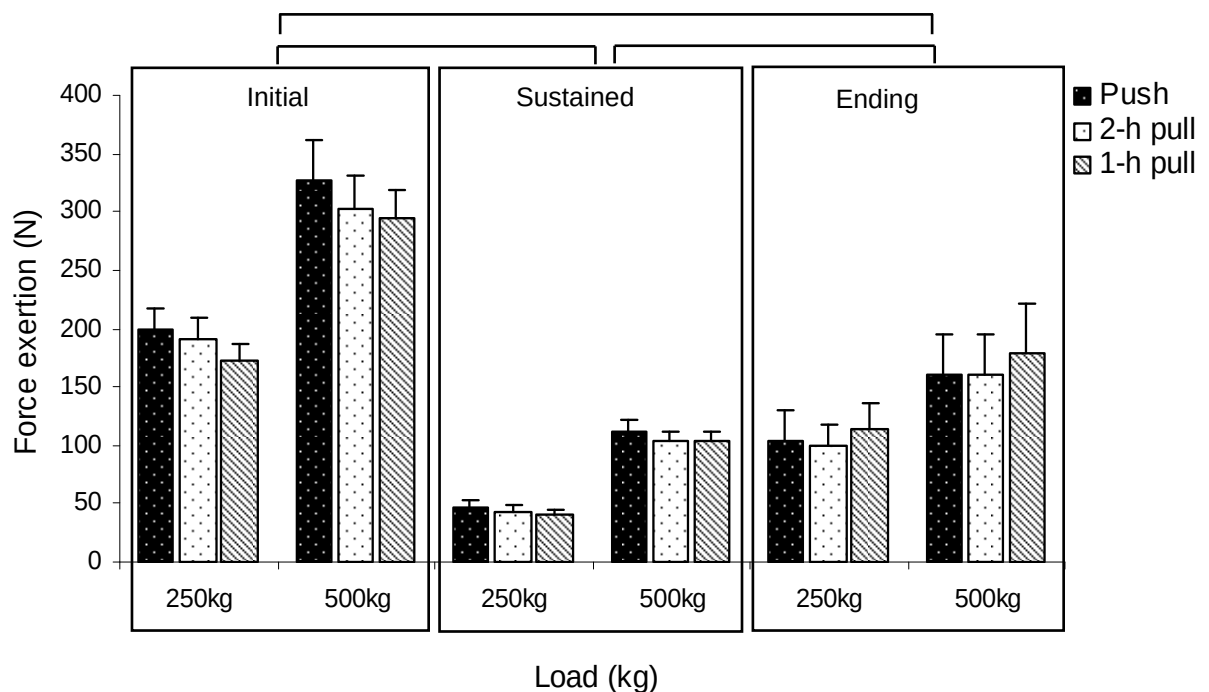


Figure 15. Differences in force output between motion phases for all conditions

Denotes statistical difference ($p < 0.05$)

The subsequent conclusion is that the high initial and ending forces are likely to result in acute and overexertion injuries if the physical capacity of the operator is exceeded. Based on this, it is assumed that injury is least likely during the sustained phase due to the lower magnitude of forces. However exerting a submaximal force for a prolonged period may contribute to fatigue and cumulative stress, a problem that must not be neglected within associated research.

SPINAL KINEMATICS

The assessment of variables related to spinal kinematics is pivotal in any ergonomic assessment of MMH, since these tasks involve considerable trunk motion, velocities and accelerations, associated with occupationally related LBDs (Marras **et al.**, 1993; 1995). Hindle **et al.** (1990) argued that the spine, being a three-dimensional structure, facilitates movement in all three planes and should be evaluated accordingly. Angular position ($^{\circ}$), velocity ($^{\circ}.\text{s}^{-1}$) and acceleration ($^{\circ}.\text{s}^{-2}$) were of interest in determining the hazards associated with the tasks under investigation and are discussed with reference to the sagittal, lateral and transverse planes. Marras **et al.** (1995) opined that maximum or peak measures of spinal kinematics provide the most suitable means of describing occupational LBD risk and therefore all investigated variables were concerned with maximum measures. In addition, in order to provide an indication of overall trunk position, mean measures were of interest regarding spinal displacements.

SPINAL DISPLACEMENTS

Mean Sagittal Position

Impact of technique

Trunk position, and specifically sagittal flexion, is a strong determinant of the risk of lower back injury, with a higher angle accentuating the danger. This is because during flexion, the lumbar spine flattens, causing the intervertebral discs to support a greater part of the load (Marras **et al.**, 1995). Mean sagittal position provided an index of trunk posture during each condition, and further indicated whether the exertion was performed primarily with the trunk in flexion or extension. Findings demonstrated that flexion (indicated by positive values), as opposed to extension of the lumbar spine predominated in all efforts, suggesting that sagittal position is potentially an area of concern. Deviations from the upright bipedal stance result in increments in the moments acting on L₅/S₁, thereby increasing shearing forces on the spine and reducing spinal tolerance (Marras, 2000). As such the more upright the posture, the less the trunk flexion and subsequently the fewer the hazards (Marras **et al.**, 2003).

Table XI. Impact of technique on mean sagittal position

Mean Sagittal Position (°)	Load (kg)		Push	2-handed pull	1-handed pull
	250	Mean	9.93	13.05	10.93
		SD	5.64	6.57	4.26
	500	Mean	10.90	17.44	13.65
		SD	5.57	6.89	4.34

 Denotes statistical difference (p<0.05)
SD=standard deviation

Although technique and load were both determinants of sagittal position, their effects were independent of each other. Pushing (mean for both loads 10.42°) and one-handed pulling (mean for both loads 12.29°) responses were lower than those of two-handed pulling. At 500kg, two-handed pulling was associated with the highest degree of flexion ($17.44 \pm 6.89^{\circ}$), and was 76% greater than the lowest response, recorded for pushing at 250kg ($9.93 \pm 5.64^{\circ}$), as seen in Table XI. At the lower load, no statistical differences existed between techniques, conversely, at the higher load, two-handed pulling responses were significantly greater than pushing (60%) and one-handed pulling (28%) responses. This may have been a result of the posture assumed not only to initiate and stop movement but also to maintain motion of the pallet jack. Moving the pallet jack at 500kg required the use of body mass to 'drive' the effort, however the position of the load relative to the individual dictated the posture adopted. While performing two-handed pulling, participants bent forward at the trunk, flexing the lumbar spine to make use of body mass due to restriction of foot movement caused by the pallet jack. During pushing and one-handed pulling however, employing body mass to move the load, was performed with less restricted foot movement and therefore without excessive lumbar flexion. In these techniques individuals were able to lean forward while maintaining the integrity of the spine.

Impact of load

At 500kg the sagittal position was 14.00° (mean for all three techniques) compared to only 11.30° (mean for all three techniques) at 250kg. This 24% difference was statistically significant and primarily due to the difference between loads during two-handed pulling. For this technique, the higher load elicited responses that

were 34% higher than those of the lower load, a difference which was statistically verified (Figure 16). These findings indicate that sagittal flexion is significantly increased with increments in load, suggesting a subsequently higher risk of injury. As such load mass moved needs to be considered when investigating push and pull tasks.

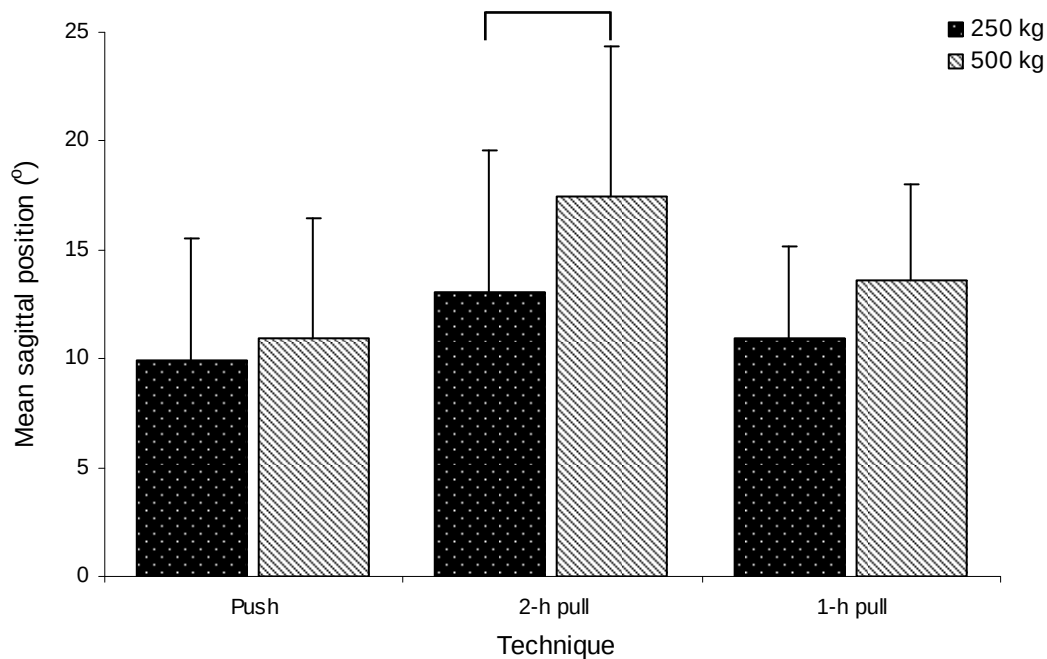


Figure 16. Impact of load on mean sagittal position

Denotes statistical difference ($p < 0.05$)

Maximum Sagittal Range of Motion

Impact of technique

Mean maximum sagittal range provided an indication of the degree of spinal displacement occurring in the sagittal plane, which is critical considering that high values may suggest that individuals are working near the limits of the spine's maximum range of motion which, according to McGill (1997) has been shown to be damaging to the discs and ligaments. Similar to results regarding mean sagittal position, technique and load independently affected peak sagittal range of motion (ROM). Averaged across loads, pushing responses were 3.47° lower than either pulling technique which were on average 14.78° . At both loads the pulling techniques, which were statistically similar (on average 12.62° for 250kg and

16.95° for 500kg) elicited responses that were significantly greater than pushing (averaged at 34% for 250kg and 28% for 500kg), shown in Table XII.

Table XII. Impact of technique on mean maximum sagittal range of motion

Mean Maximum Sagittal Range (°)	Load (kg)		Push	2-handed pull	1-handed pull	
	250	Mean	9.43	12.59	12.64	
		SD	2.97	3.73	2.97	
						
	500	Mean	13.19	17.96	15.93	
		SD	4.49	4.49	3.68	
						
						
						
	 Denotes statistical difference (p<0.05) SD=standard deviation					

The fact that one-handed pulling elicited significantly higher responses than pushing for mean maximum sagittal range, but not for mean sagittal position implies that initiating movement of the pallet jack, or bringing it to a standstill, facilitated high lumbar movement in the sagittal plane for one-handed pulling. This infers that consideration of sagittal displacement during the initial and ending phases of one-handed pulling is particularly important. Furthermore, using only mean position responses may not adequately describe the spinal kinematic responses associated with pushing and pulling.

Impact of load

Overall, load had a statistically significant impact on maximum sagittal ROM, with responses at 500kg (mean of all three techniques 15.69°) being higher than at 250kg (mean of all three techniques 11.55°). Figure 17 illustrates that for each technique, the heavier load was associated with a higher sagittal displacement because heavier loads require a greater proportion of body mass to overcome the load, facilitating the adoption of more extreme postures. With an increase in load from 250kg to 500kg, mean maximum sagittal range increased by 40%, 43% and 26% for pushing, two-handed pulling and one-handed pulling respectively. This suggests that the increase in load mass is particularly pertinent for both bilateral techniques.

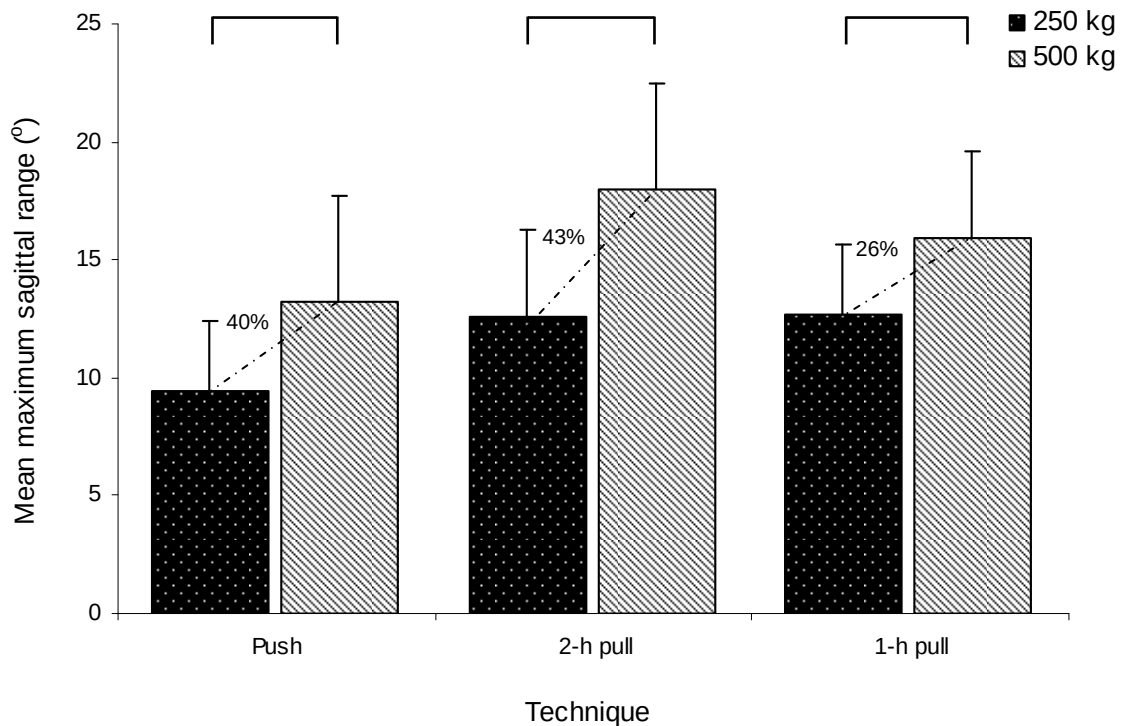


Figure 17. Impact of load on mean maximum sagittal range

┌──┐ Denotes statistical difference ($p < 0.05$)

An important finding is that sagittal positions and sagittal ranges were of similar magnitudes, which implies that a constant sagittal posture was adopted throughout the exertion and there was little cyclic movement that usually accompanies movement in the lateral and transverse planes. This may have a detrimental effect on the human body as individuals are possibly required to maintain the upper body in a static posture for an extended period.

Mean Lateral Position

Impact of technique

It is critical to acknowledge movement in the lateral plane since lateral bending has been linked to the occurrence of shear and torsion experienced at L₅/S₁, emphasising that sagittal motion and compression on the spinal structures should not be studied in isolation, as has previously been the case (Marras *et al.*, 1995). Pushing and two-handed pulling resulted in slight trunk bending to the right (averaged at 1.22° for both loads and indicated by positive values), while one-

handed pulling was associated with slight bending to the left (averaged at -1.12° for both loads), primarily due to one-handed pulling at 250kg (Table XIII).

Table XIII. Impact of technique on mean lateral position

Mean Lateral Position ($^{\circ}$)	Load (kg)		Push	2-handed pull	1-handed pull
	250	Mean	0.99	1.35	-2.28
		SD	1.72	1.94	-3.53
	500	Mean	1.07	1.47	0.04
		SD	2.00	2.34	5.04

 Denotes statistical difference ($p < 0.05$)
 SD=standard deviation

The highest responses were observed for one-handed pulling at 250kg ($-2.28 \pm 3.53^{\circ}$) and the lowest for one-handed pulling at 500kg ($0.04 \pm 5.04^{\circ}$). Although differences between techniques appear to be statistically significant, absolute values are close to zero, suggesting that mean lateral position approximated the natural curve of the lumbar spine. Differences are thus probably not practically significant and can be attributed to the cyclic nature of lateral position as a result of walking (Figure 18). At 500kg, all techniques produced similar lateral positions (on average 0.86°), once again with all absolute values close to zero.

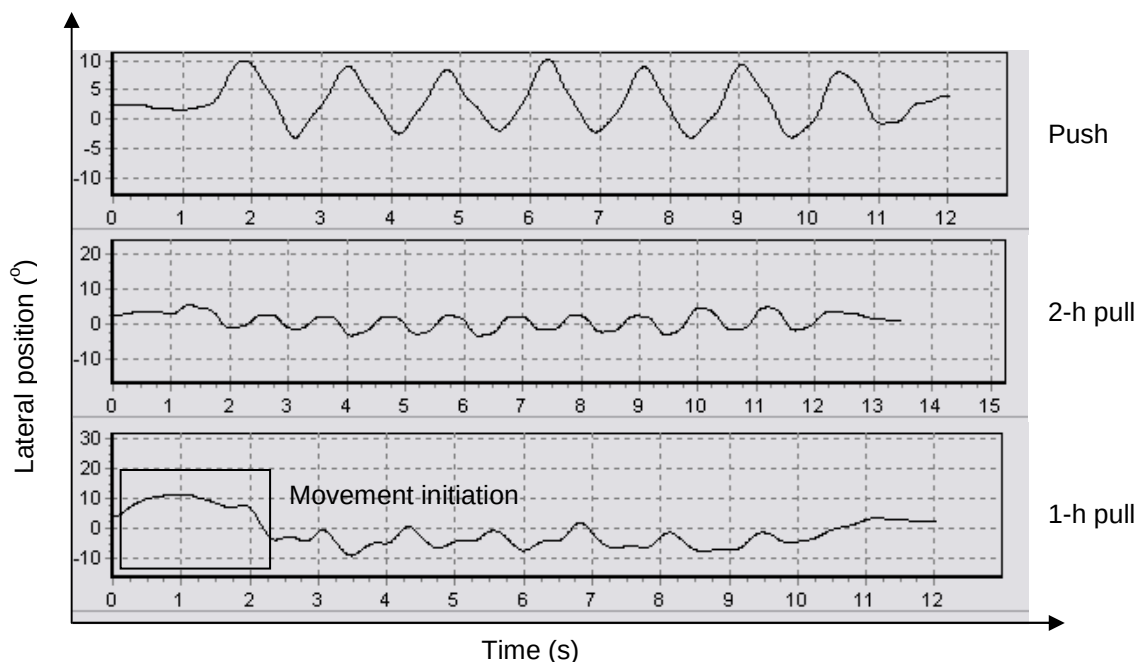


Figure 18. Cyclic nature of lateral displacement due to walking (at 500kg)

Impact of load

Although the effect of load on lateral position was significant, with the higher load (mean for all three techniques 0.87°) eliciting higher responses than the lower load (mean for all three techniques 0.21°), the values are small and close to zero. It can therefore be concluded that overall, deviations from the neutral posture were small and that load only marginally affected this relationship. It is important to note that the interaction between technique and load influenced lateral position, suggesting that the impact that technique has on lateral position is dependent on the load being moved.

Maximum Lateral Range of Motion

Impact of technique

The nature of activities under investigation meant that displacement of the spine in the lateral plane may pose a hazard, which prompted assessment of maximum lateral range. Overall, one-handed pulling (mean for both loads 17.12°) elicited significantly greater responses than pushing (mean for both loads 10.16°) and two-handed pulling (mean for both loads 8.80°). Due to the asymmetrical nature of one-handed pulling, which entails forward walking with the load positioned behind the body, the greatest maximum lateral range was evidenced for this technique under both loads ($14.81 \pm 3.78^{\circ}$ for 250kg and $19.42 \pm 4.97^{\circ}$ for 500kg), depicted in Table XIV. The magnitudes were significantly higher (on average 70% for 250kg and 90% for 500kg respectively) than either of the bilateral techniques. Furthermore, there was no statistical difference between pushing and two-handed pulling responses at either load due to the symmetric nature of the bilateral conditions.

As the same differences did not exist for mean lateral position at the high load, maximum lateral ROM during one-handed pulling at 500kg is perhaps largely influenced by the posture adopted while initiating or ending movement of the pallet jack. Shown in Figure 18, large lateral deviations from the upright posture occurred at the beginning of the exertion. However while maintaining motion, the lumbar spine assumed a position closer to its neutral posture, accounting for the small overall lateral position (0.04°). Importantly, maximum lateral range for one-handed

pulling at the low load was considerably higher than responses for either bilateral technique at the high load, emphasising the role that technique plays on displacement in the lateral plane. Shirazi-Adl (1989) suggests that the subsequent increased lateral bending leads to higher lateral shear forces, which essentially compromise the integrity of the spine.

Table XIV. Impact of technique on mean maximum lateral range of motion

Mean Maximum Lateral Range (°)	Load (kg)		Push	2-handed pull	1-handed pull
	250	Mean	9.13	8.31	14.81
		SD	2.20	2.39	3.78
	500	Mean	11.18	9.28	19.42
		SD	2.93	3.51	4.97

└─┘ Denotes statistical difference (p<0.05)
SD=standard deviation

Impact of load

The overall effect of load on lateral ROM resulted in the higher load (mean for all three techniques 13.30°) eliciting higher responses than the lower load (mean for all three techniques 10.75°), due primarily to one-handed pulling where statistically significant differences were found (Figure 19), with lateral range at 500kg being 31% greater than at the lower load. There was no load impact (p>0.05) for pushing and two-handed pulling, even though there was a difference of 2° between the pushing responses. The effect of load is therefore of particular concern during one-handed pulling, because as load mass increases, so too does lateral ROM, and subsequently the hazards associated with injury to the lower back. Like lateral position, it must be acknowledged that the interplay between technique and load influenced lateral ROM, as the impact of load on this variable was dependent on the technique employed.

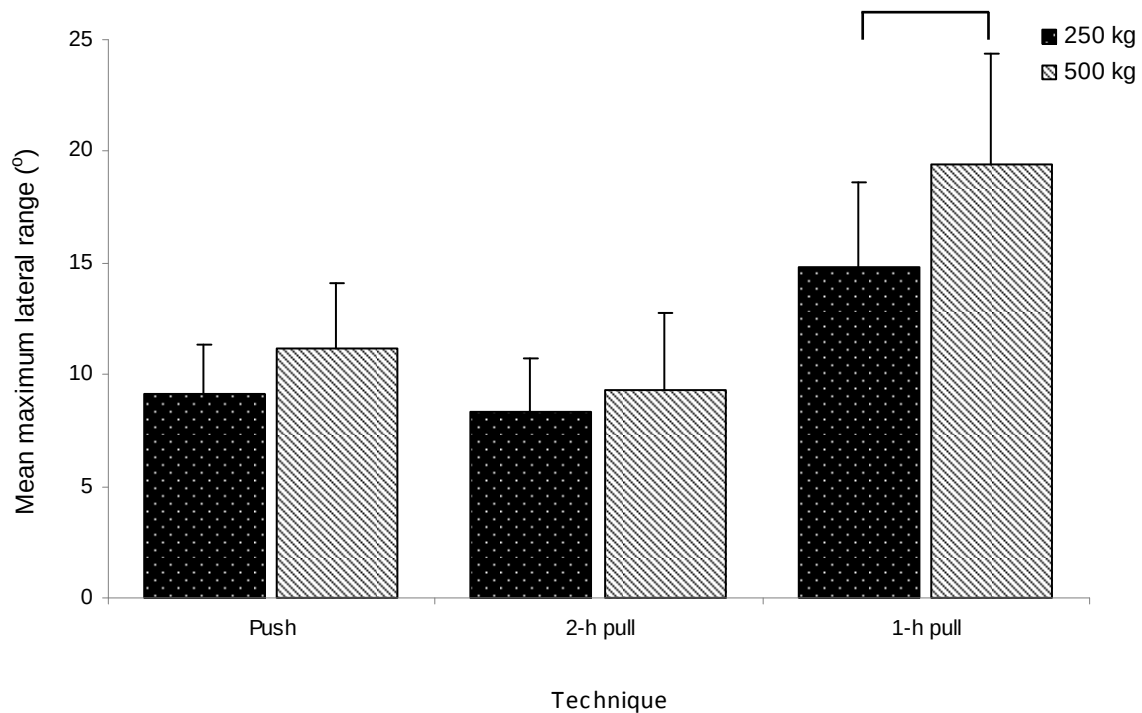


Figure 19. Impact of load on mean maximum lateral range

Denotes statistical difference ($p < 0.05$)

Mean Twisting Position

Impact of technique

Twisting has been reported to be related to lower back morbidity (Bigos **et al.**, 1986; Ferguson **et al.**, 1992) due to the shear and torsion forces imposed on the spine (Marras **et al.**, 1995). Movement in the transverse plane hence provides an index of potential risk.

Table XV. Impact of technique on mean twisting position

Mean Twisting Position (°)	Load (kg)		Push	2-handed pull	1-handed pull
	250	Mean	-1.26	-0.73	18.69
		SD	3.85	4.17	6.07
	500	Mean	-0.97	-0.99	16.69
		SD	3.60	4.46	6.63

Denotes statistical difference ($p < 0.05$)
SD=standard deviation

Only technique was evidenced to have a significant impact, with pushing and two-handed pulling resulting in a mean twisting position close to neutral, while one-handed pulling caused a substantial right twist (mean for both loads 17.69°). The absolute values for the bilateral conditions were close to zero at both loads (Table XV), inferring that the postures assumed approximated the normal curve of the lumbar spine. This was possibly due to the symmetric nature of both bilateral techniques and hence any twisting that occurred could be attributed to the cyclic nature of spinal twisting due to walking. In contrast, one-handed pulling necessitated twisting of the spine to facilitate walking forward while pulling the load behind the body, thereby eliciting greater responses (18.69° for 250kg and 16.69° for 500kg) and hence, greater torsion forces than the other two techniques.

Impact of load

Load was not found to have any impact on twisting position; at 250kg twisting position was 5.57° (mean for all three techniques) and at 500kg 4.91° (mean for all three techniques). The most critical factor contributing to overall trunk postures in the transverse plane is therefore technique, whereby those that promote symmetrical as opposed to asymmetrical postures elicit much lower transverse displacements.

Maximum Twisting Range of Motion

Impact of technique

Unlike mean twisting position, both technique and load influenced maximum twisting ROM, although they were not interactive. The overall impact of technique revealed that pushing (mean for both loads 18.62°) and two-handed pulling (mean for both loads 13.94°) responses were significantly lower than those of one-handed pulling (mean for both loads 36.50°). Furthermore, twisting ROM was lower for two-handed pulling compared to pushing, a difference which was statistically substantiated.

Table XVI. Impact of technique on mean maximum twisting range of motion

Load (kg)		Push	2-handed pull	1-handed pull
250	Mean	17.06	13.34	35.27
	SD	4.60	4.13	7.90
500	Mean	20.17	14.53	37.74
	SD	5.27	4.58	7.51

 Denotes statistical difference (p<0.05)
 SD=standard deviation

Referring to Table XVI, one-handed pulling responses at both loads (35.27° and 37.74° for 250kg and 500kg respectively) were significantly higher than those associated with the other techniques. Importantly, one-handed pulling at the low load produced higher values compared to the bilateral techniques at the high load, indicating that technique has a profound impact on twisting ROM. Equally important is that both bilateral techniques caused sizeable displacements in the transverse plane, possibly as a result of the cyclic spinal twisting that inevitably occurs during walking (Figure 20). According to Figure 20, initiation of movement is important in increasing twisting ROM for pushing, suggesting that this phase is of greatest concern. At 500kg, pushing responses were significantly higher (39%) than those for two-handed pulling, but with no statistical difference at 250kg.

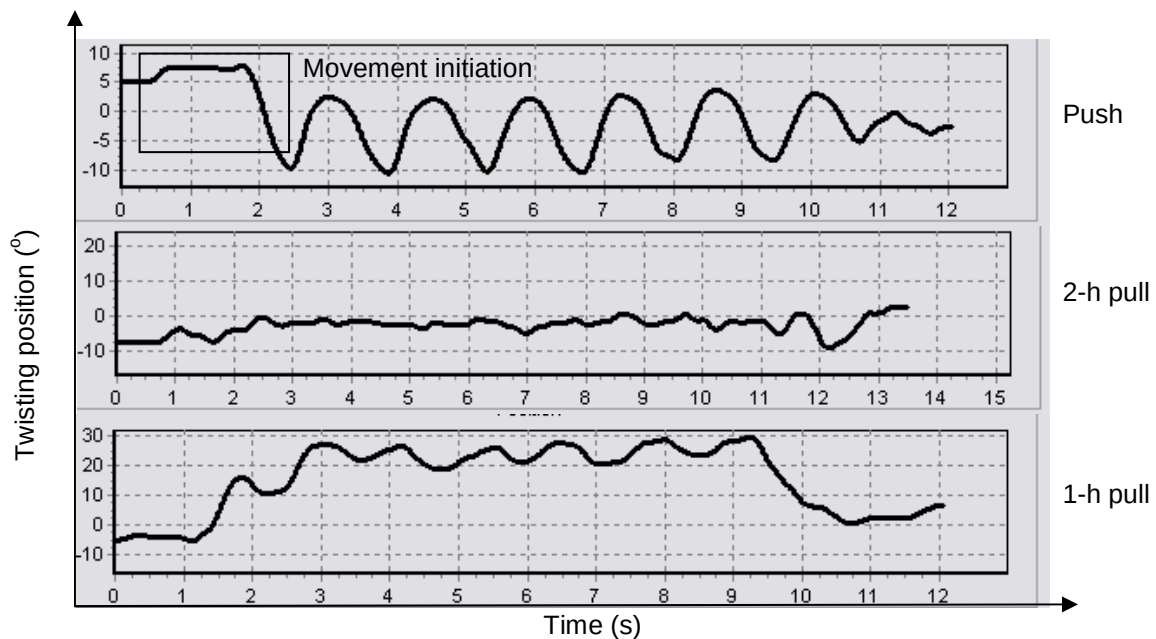


Figure 20. Cyclic nature of spinal twisting due to walking (at 500kg)

Impact of load

Load affected twisting ROM (Figure 21), with the higher load producing higher responses (mean of all three techniques 24.15°) than the lower load (mean of all three techniques 21.89°). For each individual technique, however, there were no statistically significant differences between loads. It is therefore evident that pushing and pulling technique plays a more important role in determining twisting angle and ROM than the load moved.

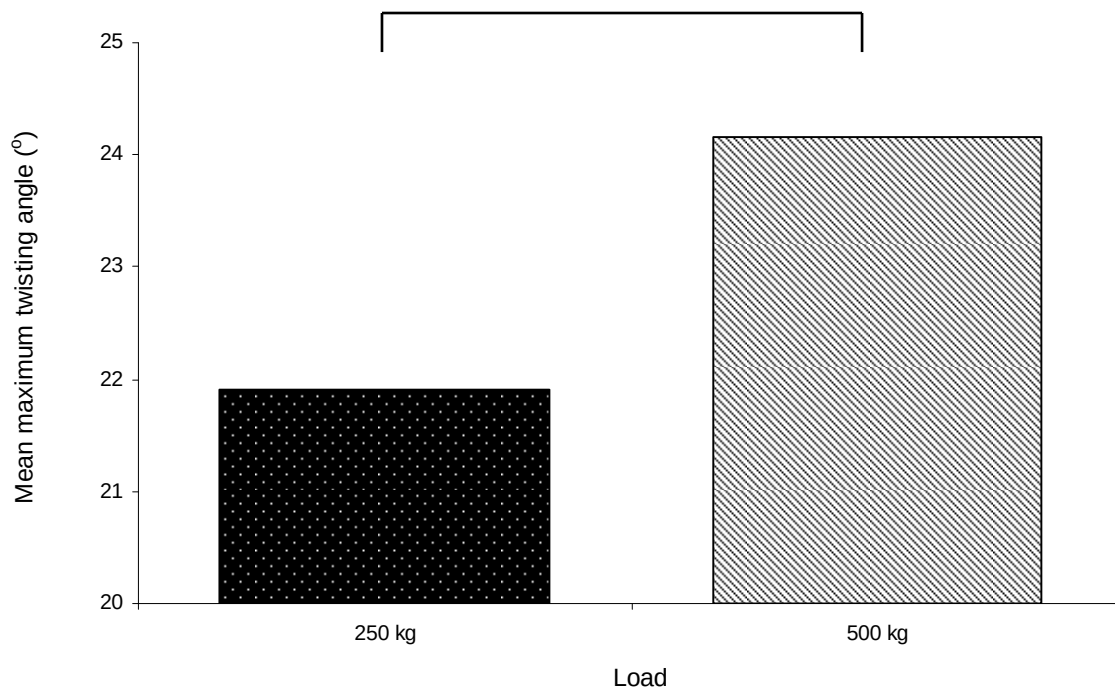


Figure 21. Impact of load on maximum twisting angle

┌──┐ Denotes statistical difference ($p < 0.05$)

SPINAL VELOCITIES

Maximum Sagittal Velocity

Impact of technique

According to Marras **et al.** (1993; 1995), velocity is the principal trunk motion factor to consider for risk prediction compared to maximum or minimum position, ROM or even acceleration. Although spinal velocities for pushing and pulling have largely been overlooked, lifting investigations have reported that increases in trunk velocity are related to subsequent increases in spinal loading (McGill and Norman,

1985). For this reason, mean maximum sagittal velocities in all three planes were analysed.

Table XVII. Impact of technique on mean maximum sagittal velocity

Mean Maximum Sagittal Velocity ($^{\circ}\cdot s^{-1}$)	Load (kg)		Push	2-handed pull	1-handed pull
	250	Mean	17.05	20.85	20.54
		SD	4.71	5.35	5.62
	500	Mean	23.16	25.14	25.86
		SD	6.66	8.75	6.10

┌ Denotes statistical difference ($p < 0.05$)
SD=standard deviation

Similar to the sagittal position and maximum sagittal ROM, technique and load separately influenced mean maximum sagittal velocity. Overall, the impact of technique (Figure 22) on this variable suggested that pushing responses (mean for both loads $20.11^{\circ}\cdot s^{-1}$) were statistically lower than responses during either pulling technique (mean for both techniques at both loads $23.10^{\circ}\cdot s^{-1}$). Irrespective of load, pushing ($17.05 \pm 4.71^{\circ}\cdot s^{-1}$ for 250kg and $23.16 \pm 6.66^{\circ}\cdot s^{-1}$ for 500kg) elicited the lowest responses. However, no statistically significant differences were apparent between techniques at either load, as shown in Table XVII.

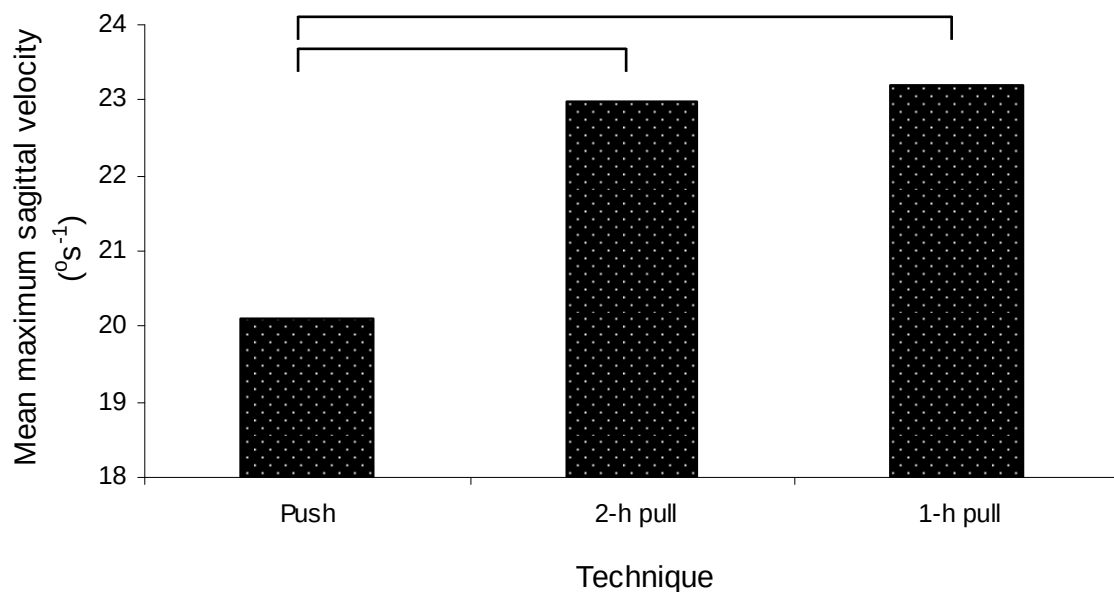


Figure 22. Impact of technique on mean maximum sagittal velocity

┌ Denotes statistical difference ($p < 0.05$)

Impact of load

Load had a significant impact on maximum sagittal velocity, with the higher load producing higher responses (mean for all three techniques $24.72^{\circ}.\text{s}^{-1}$) than the lower one (mean of all three techniques $19.48^{\circ}.\text{s}^{-1}$). For each technique, statistical differences were evidenced between loads (Figure 23), with the most profound being for pushing, where doubling the load mass caused an increase of 36% from the lower to the higher response. The increase was smaller for both pulling techniques; 21% for two-handed pulling and 26% for one-handed pulling.

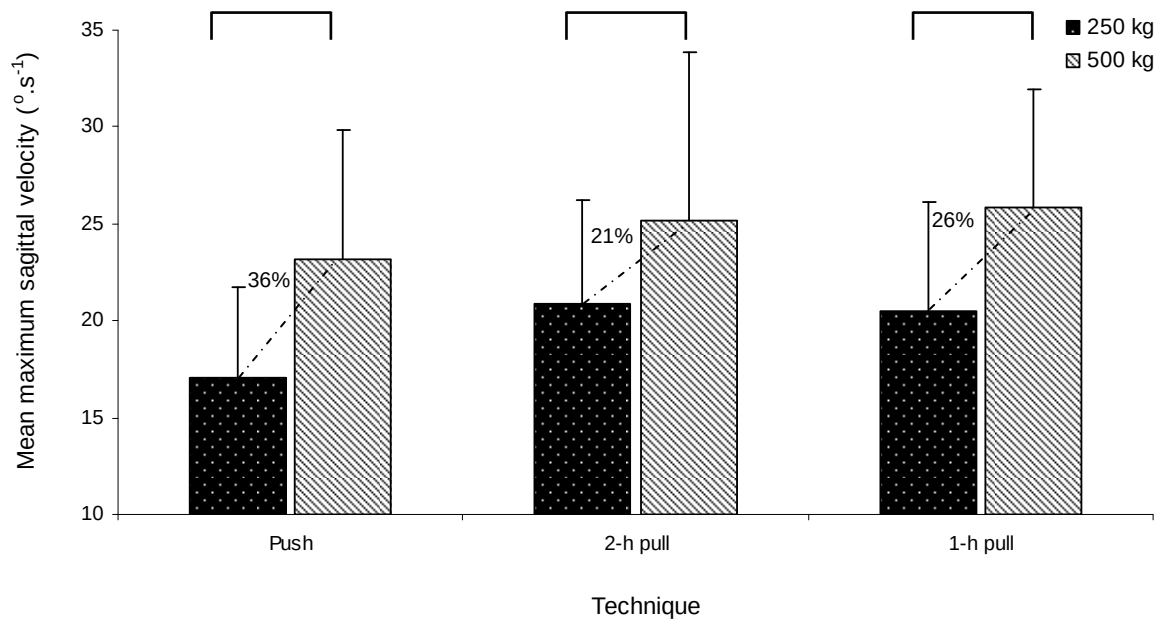


Figure 23. Impact of load on mean maximum sagittal velocity

┌─┐ Denotes statistical difference ($p < 0.05$)

Maximum Lateral Velocity

Impact of technique

High maximum lateral velocities imply that tasks expose individuals to rapid sideways bending, suggesting task asymmetry (Marras **et al.**, 2003). Similar to mean lateral position and mean maximum lateral ROM, technique and load both affected the maximum lateral velocity, but with no interaction effect. Aggregated across loads, significant differences existed between all techniques, where one-handed pulling (mean for both loads $31.10^{\circ}.\text{s}^{-1}$) was associated with the highest response and two-handed pulling, the lowest (mean for both loads $21.15^{\circ}.\text{s}^{-1}$).

At each load, technique influenced lateral velocity, as shown in Table XVIII. Given the asymmetrical nature of one-handed pulling, it is not surprising that this technique was associated with the highest maximum lateral velocities. At 250kg, mean maximum lateral velocity for one-handed pulling ($29.07 \pm 7.26^{\circ} \cdot s^{-1}$) was found to be 36% higher than that of two-handed pulling, yet both were statistically similar to pushing responses. At 500kg, velocities for both pushing and one-handed pulling were significantly greater by approximately 47% compared to responses for two-handed pulling. Essentially, in terms of maximum lateral velocity, one-handed pulling is accompanied by the highest risk and two-handed pulling, the lowest.

Table XVIII. Impact of technique on mean maximum lateral velocity

Mean Maximum Lateral Velocity ($^{\circ} \cdot s^{-1}$)	Load (kg)		Push	2-handed pull	1-handed pull
	250	Mean	25.30	21.33	29.07
		SD	6.55	7.65	7.26
	500	Mean	28.35	20.96	33.12
		SD	8.04	7.30	8.99

┌ Denotes statistical difference ($p < 0.05$)
SD=standard deviation

Impact of load

Although the higher load was associated with higher mean maximum lateral velocities (mean of all three techniques $27.48^{\circ} \cdot s^{-1}$) compared with the lower one (mean of all three techniques $25.23^{\circ} \cdot s^{-1}$), shown in Figure 24, there were no statistical differences between loads at each technique. Velocities of both pushing and one-handed pulling resulted in slight increases, while two-handed pulling was related to a small decrease when the load was doubled, all of which resulted in differences corresponding to less than $4.05^{\circ} \cdot s^{-1}$.

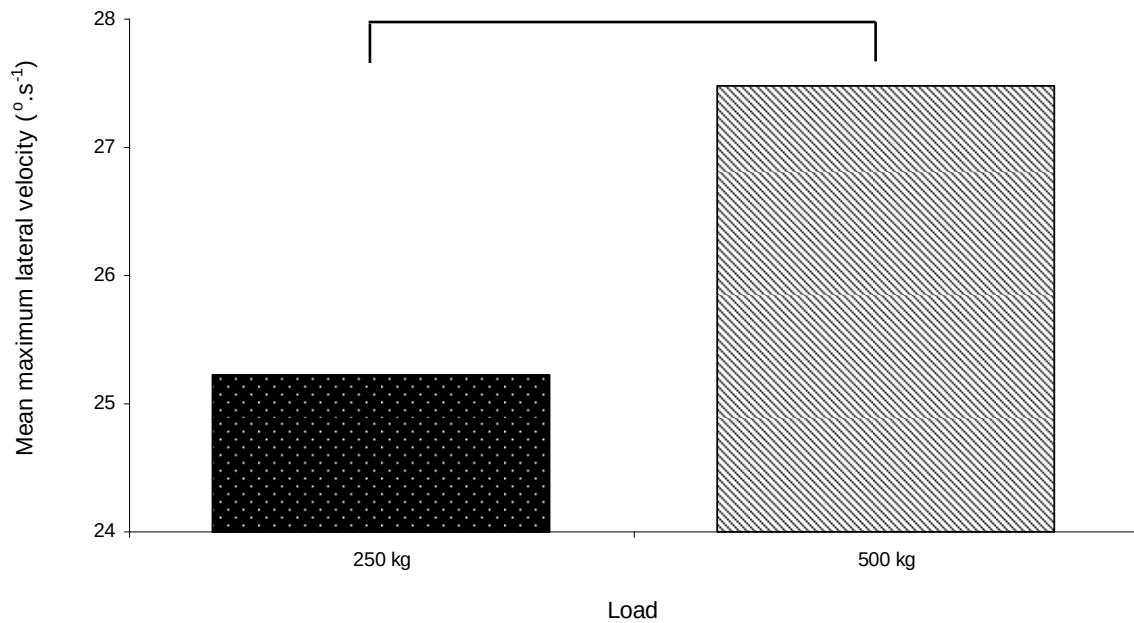


Figure 24. Impact of load on maximum lateral velocity

Denotes statistical difference ($p < 0.05$)

Maximum Twisting Velocity

Impact of technique

Jobs that are typically asymmetrical in nature evidence high maximum twisting velocities and require swift right and left movements in the transverse plane, resulting in considerable shear and compressive forces between the vertebrae (Davis and Marras, 2000). Unlike the sagittal and lateral velocities, only technique significantly affected maximum twisting velocity. Overall, statistical differences were evidenced between all techniques, where mean maximum twisting velocity for two-handed pulling (mean for both loads $30.35^{\circ} \cdot s^{-1}$) was the lowest and that of one-handed pulling, the highest (mean for both loads $58.00^{\circ} \cdot s^{-1}$). In congruence with the twisting position and twisting ROM, maximum twisting velocity for one-handed pulling was associated with the highest responses at both loads ($58.14 \pm 11.47^{\circ} \cdot s^{-1}$ at 250kg and $57.85 \pm 12.87^{\circ} \cdot s^{-1}$ at 500kg), while the lowest related to two-handed pulling ($30.58 \pm 9.55^{\circ} \cdot s^{-1}$ at 250kg and $30.12 \pm 8.26^{\circ} \cdot s^{-1}$ at 500kg), depicted in Table XIX. Irrespective of load, one-handed pulling responses were at least $13.87^{\circ} \cdot s^{-1}$ higher than those of either of the bilateral techniques, while pushing responses were at least $8.60^{\circ} \cdot s^{-1}$ greater than two-handed pulling responses. Evidently, in terms of maximum twisting velocity one-handed pulling,

associated with the greatest transverse velocities and therefore torsion forces poses the greatest risk.

Table XIX. Impact of technique on mean maximum twist velocity

Mean Maximum Twist Velocity ($^{\circ} \cdot s^{-1}$)	Load (kg)		Push	2-handed pull	1-handed pull
	250	Mean	39.18	30.58	58.14
		SD	9.25	9.55	11.47
	500	Mean	43.98	30.12	57.85
		SD	9.31	8.26	12.87

 Denotes statistical difference ($p < 0.05$)
 SD=standard deviation

Impact of load

Only small differences, with the largest of these being $4.80^{\circ} \cdot s^{-1}$, were evident in maximum twisting velocity between 250kg and 500kg indicating that increasing load does not significantly affect twisting velocity and that other factors such as push/pull technique are more important.

SPINAL ACCELERATIONS

Maximum Sagittal Acceleration

Impact of technique

Given that the velocity of the spine will not remain constant while performing a task, maximum accelerations are crucial to acknowledge, with evidence suggesting that acceleration may affect spinal loading (Granata and Marras, 1995). Both, technique and load were instrumental in determining maximum sagittal acceleration, albeit with no interaction. Considering the overall effect of technique, two-handed pulling resulted in a $19.58^{\circ} \cdot s^{-2}$ (aggregated for both loads) higher mean maximum sagittal acceleration than pushing, but both techniques elicited responses that were statistically similar to that of one-handed pulling. Although pushing responses were most conservative at both loads, only at 250kg was there a significant difference between techniques (Table XX), where maximum accelerations for two-handed pulling were 29% greater than those of pushing. Since no differences existed at 500kg, the role that technique plays in

determining maximum sagittal acceleration becomes less profound at higher loads.

Table XX. Impact of technique on mean maximum sagittal acceleration

Mean Maximum Sagittal Acceleration ($^{\circ}\cdot s^{-2}$)	Load (kg)		Push	2-handed pull	1-handed pull
	250	Mean	125.89	162.46	141.34
		SD	32.23	40.63	38.09
	500	Mean	175.40	177.99	187.17
		SD	54.86	71.93	46.01

┌─┐ Denotes statistical difference ($p<0.05$)
SD=standard deviation

Impact of load

Statistical differences evidenced between loads were primarily due to pushing and one-handed pulling (Figure 25), where moving the heavy load was accompanied by a 39% and 32% increase in maximum sagittal acceleration respectively compared to moving 250kg. Interestingly, load did not appear to significantly increase maximum sagittal acceleration for two-handed pulling, although it must be noted that at 250kg, responses for this technique were higher than those of the other techniques, perhaps accounting for the responses.

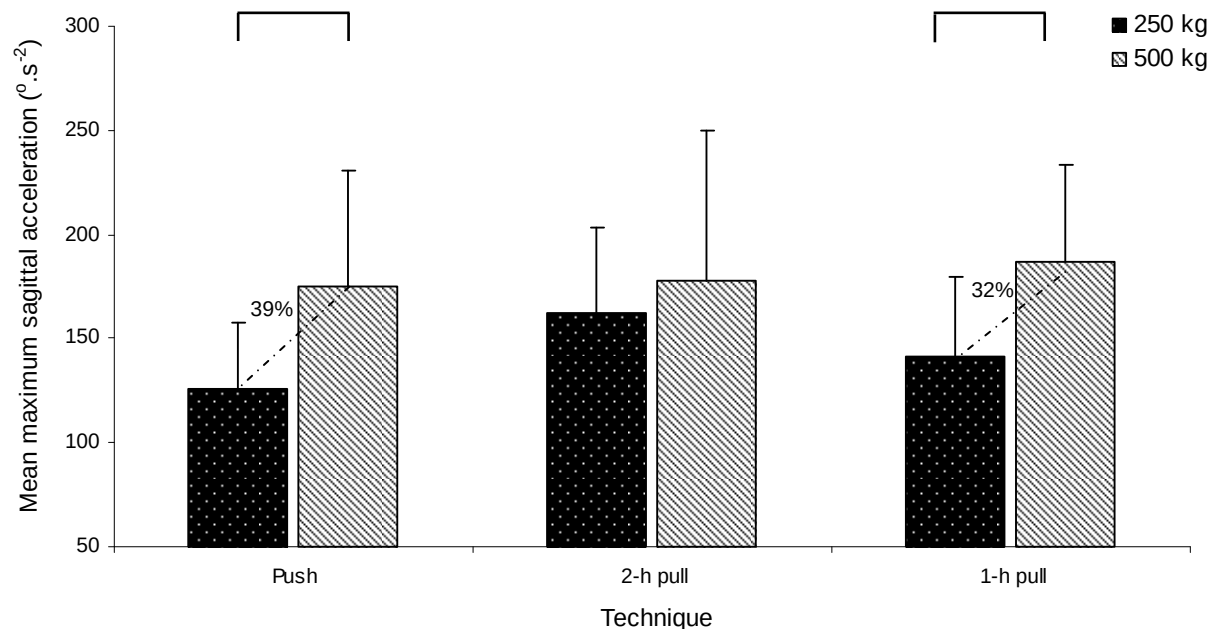


Figure 25. Impact of load on mean maximum sagittal acceleration

┌─┐ Denotes statistical difference ($p<0.05$)

Maximum Lateral Acceleration

Impact of technique

Unlike lateral position, maximum ROM and velocity, only technique was influential in determining maximum lateral acceleration. The overall effect suggested that statistical differences were apparent between each technique. One-handed pulling (mean for both loads $232^{\circ}.\text{s}^{-2}$) resulted in the greatest response and was 38% higher than the lowest response, occurring during two-handed pulling (mean for both loads $168^{\circ}.\text{s}^{-2}$).

Table XXI. Impact of technique on mean maximum lateral acceleration

Mean Maximum Lateral Acceleration ($^{\circ}.\text{s}^{-2}$)	Load (kg)		Push	2-handed pull	1-handed pull
	250	Mean	193.78	172.44	218.88
		SD	49.37	57.56	52.97
	500	Mean	206.07	163.54	245.19
		SD	53.92	51.99	62.11

┌ Denotes statistical difference ($p < 0.05$)
SD=standard deviation

In accordance with maximum lateral ROM and velocity, one-handed pulling resulted in the highest maximum lateral accelerations, regardless of load ($219 \pm 53^{\circ}.\text{s}^{-2}$ for 250kg and $245 \pm 62^{\circ}.\text{s}^{-2}$ for 500kg) while two-handed pulling was associated with the lowest ($172 \pm 58^{\circ}.\text{s}^{-2}$ for 250kg and $164 \pm 52^{\circ}.\text{s}^{-2}$ for 500kg). At 250kg, responses for one-handed pulling were significantly greater (27%) than those of two-handed pulling, but both these techniques were statistically similar to pushing (Table XXI). However an increase in load to 500kg was associated with greater differences between techniques with all three techniques being significantly different.

Impact of load

Maximum lateral accelerations were similar for the two loads, with responses of $195^{\circ}.\text{s}^{-2}$ (mean for all three techniques) and $205^{\circ}.\text{s}^{-2}$ (mean for all three techniques) for 250kg and 500kg respectively. Although not statistically significant, an increase in load for two-handed pulling was associated with a reduction in lateral acceleration, while the two other techniques evidenced small increases.

Maximum Twisting Acceleration

Impact of technique

Similar to mean position and maximum velocity in the transverse plane, only technique had an impact on maximum twisting acceleration. Statistical differences were evident between all techniques, regardless of load, where one-handed pulling responses (mean for both loads $378^{\circ} \cdot s^{-2}$) were the highest and those of two-handed pulling, the lowest (mean for both loads $231^{\circ} \cdot s^{-2}$).

Table XXII. Impact of technique on mean maximum twist acceleration

Maximum Twist Acceleration ($^{\circ} \cdot s^{-2}$)	Load (kg)		Push	2-handed pull	1-handed pull
	250	Mean SD	297.21 74.36	239.80 65.22	362.20 64.79
	500	Mean SD	322.14 72.65	221.61 50.73	393.84 80.17

┌ Denotes statistical difference ($p < 0.05$)
SD=standard deviation

Depicted in Table XXII, technique had a considerable impact on peak twisting accelerations at both loads. Due to the twisting displacement and velocity being highest during one-handed pulling, the maximum accelerations were also highest during performance of this technique ($362 \pm 65^{\circ} \cdot s^{-2}$ for 250kg and $394 \pm 80^{\circ} \cdot s^{-2}$ for 500kg). Correspondingly two-handed pulling responses were the lowest, returning values significantly lower than the other two techniques. Therefore in the transverse plane, it is apparent that one-handed pulling places individuals at the greatest risk and two-handed pulling, the least.

Impact of load

Regarding maximum twisting acceleration, the impact of load was not statistically significant, with responses at 250kg being on average $300^{\circ} \cdot s^{-2}$ (mean for all three techniques) and $313^{\circ} \cdot s^{-2}$ (mean for all three techniques) at 500kg. Generally, responses at 500kg were only approximately 4% higher than those at 250kg. Similar to maximum lateral acceleration, an increase in load resulted in a reduction in accelerations for two-handed pulling and small increases for pushing and one-handed pulling.

MUSCLE ACTIVITY

When comparing the strain of specific muscles under varying conditions with the assumption that certain postures may negatively impact on them, electromyography (EMG) proves to be invaluable (Marras, 1992), providing an indication of local muscle recruitment through the measurement of electrical signals produced by the muscles during contractions (Göbel, 2005). Dynamic pushing/pulling typically involve static and dynamic muscular contractions, with the former occurring in the trunk and upper extremities (Garcin **et al.**, 1996; Hoozemans **et al.**, 1998) and the latter in the lower limbs during walking. For a comprehensive understanding of the results obtained, the muscles under investigation have been grouped according to body region: the arm (brachioradialis, triceps brachii), shoulder (anterior, medial and posterior deltoids) and back (upper fibres of trapezius, latissimus dorsi and erector spinae).

ARM MUSCLES

Impact of technique

Regarding brachioradialis, muscle activity for one-handed pulling (mean for both loads 12.43%MVC) was found to be the highest compared to the other two techniques. In addition, pushing (mean for both loads 5.18%MVC) elicited higher overall responses than two-handed pulling (mean for both loads 3.42%MVC). At 250kg, significant differences were found; one-handed pulling (9.65%MVC) was approximately three times greater than either of the bilateral techniques (on average 3.32%MVC), which were statistically alike, shown in Table XXIII. Similar statistical differences were apparent at the heavy load, with one-handed pulling being associated with the highest muscle activity (15.20%MVC), suggesting that this smaller muscle must work at a higher percentage of its maximal capacity compared to the muscles used when both arms are involved simultaneously (during both bilateral techniques), placing it at a higher risk of overstrain. At 500kg, pushing responses were also found to be significantly higher compared with those for two-handed pulling. Thus two-handed pulling evokes the least strain in brachioradialis.

Table XXIII. Muscle activity of brachioradialis and triceps brachii (% of MVC)

<i>Load (kg)</i>			<i>Push</i>	<i>2-handed pull</i>	<i>1-handed pull</i>
Brachioradialis	250	Mean	3.67	2.96	9.65
		SD	2.87	2.80	7.49
	500	Mean	6.69	3.87	15.20
		SD	5.94	3.20	16.58
Triceps brachii	250	Mean	7.97	8.82	5.29
		SD	3.38	4.97	3.44
	500	Mean	10.81	13.55	11.35
		SD	4.90	7.42	7.61

┌─┐ Denotes statistical difference (p<0.05)
SD=standard deviation

Unlike brachioradialis, technique and load interacted to influence the muscle activity of the triceps brachii. While brachioradialis was associated with the highest muscle activity during one-handed pulling, overall, the triceps brachii were least active during this technique indicating that different muscle groups are strained during different techniques. At 250kg, technique had a statistical impact, with responses of both bilateral techniques (mean for both 8.40%MVC) being 59% higher than those of one-handed pulling. The differences between muscle activities for each technique were much smaller at 500kg, implying that the impact of technique became less influential, and as such, no significant differences existed at this load (mean of all three techniques 11.90%MVC).

Impact of load

For both brachioradialis and triceps, the heavier load elicited higher responses than the lighter load, aggregated across all three techniques. According to Figure 26 muscle activity at 500kg was significantly higher (82%) for brachioradialis during pushing, but not for either pulling technique. Although muscle activity of brachioradialis is always high and of concern during one-handed pulling, as the

load increases, the risk associated with pushing is also augmented. Therefore, technique is largely influential on muscle activity of brachioradialis during one-handed pulling, whereas load has a greater impact on its muscle activity during pushing.

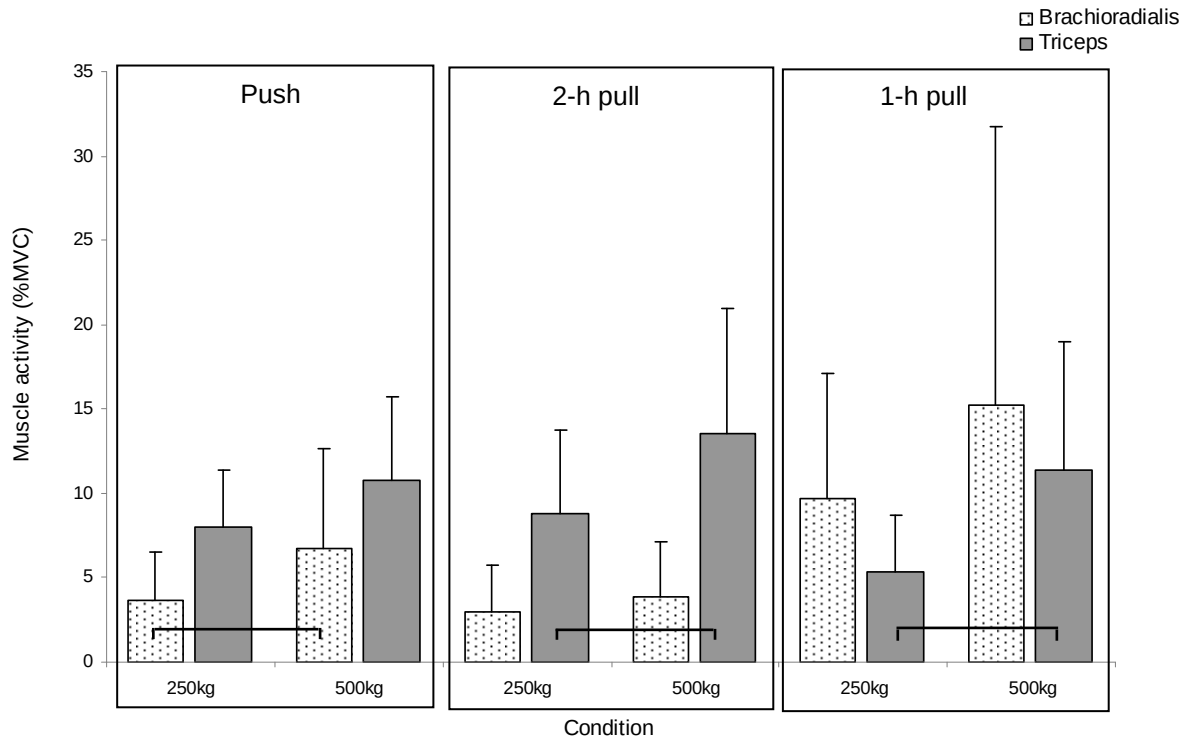


Figure 26. Muscle activity of brachioradialis and triceps brachii

— Denotes statistical difference ($p < 0.05$)

In contrast to brachioradialis, muscle activity of the triceps was statistically higher at 500kg compared to 250kg during two-handed (54%) and one-handed pulling (115%). Although one-handed pulling at 250kg was associated with the lowest activity, the difference between responses at higher loads diminishes. Therefore, the influence of technique on muscle activity was dependent on the load moved.

SHOULDER MUSCLES

Impact of technique

With reference to the shoulder muscles (Table XXIV), technique and load had a significant influence on muscle activity. This effect was interactional for the anterior and medial, but not posterior deltoid. Considering the anterior deltoid, the impact of load on muscle activity was dependent on the technique used, while the

opposite was true for the medial deltoid. Significant differences were present for the muscle activity of the anterior and medial deltoids between all three techniques (aggregated for both loads), where pushing was found to elicit the highest muscle activity and two-handed pulling, the lowest. On the contrary, overall muscle activity of the posterior deltoid was highest for one-handed pulling and lowest for pushing. Responses for both of these techniques were however statistically similar to those associated with two-handed pulling. The impact of technique on the muscle activity of each deltoid differs somewhat because functionally, they are responsible for different actions.

The anterior deltoid, regardless of the load moved, evidenced significant differences for all three techniques with pushing resulting in the highest activation levels (7.12%MVC and 22.96%MVC for 250kg and 500kg respectively) and two-handed pulling the lowest, at only 2.70%MVC and 3.88%MVC for 250kg and 500kg respectively. Regarding the medial deltoid, similar statistical differences were evident at 500kg. However at 250kg, pushing and one-handed pulling, which were statistically similar (mean for both 3.64%MVC) produced higher responses than two-handed pulling (2.07%MVC). Muscle activity of the posterior deltoid was highest during one-handed pulling at both loads (7.39%MVC and 11.63%MVC for 250kg and 500kg respectively). At 250kg, this technique produced significantly greater responses than either bilateral technique by on average 2.3%MVC. However at 500kg, although significantly higher than pushing, one-handed pulling responses were similar to those for two-handed pulling.

Table XXIV. Muscle activity of deltoid muscles (% of MVC)

<i>Load (kg)</i>			<i>Push</i>	<i>2-handed pull</i>	<i>1-handed pull</i>
Anterior deltoid	250	Mean	7.12	2.70	4.06
		SD	4.53	2.12	2.60
	500	Mean	22.96	3.88	6.48
		SD	14.22	3.40	3.11
Medial deltoid	250	Mean	3.90	2.07	3.37
		SD	2.72	1.23	1.74
	500	Mean	9.80	2.53	3.72
		SD	6.11	1.52	2.04
Posterior deltoid	250	Mean	4.50	5.67	7.39
		SD	2.19	3.60	3.17
	500	Mean	6.97	9.85	11.63
		SD	3.50	6.72	5.60

┌─┐ Denotes statistical difference (p<0.05)
SD=standard deviation

Impact of load

All three heads of the deltoid evidenced higher overall muscle activation levels at the higher load compared to at 250kg. Referring to the anterior deltoid, muscle activity was significantly higher at 500kg compared to 250kg during pushing and one-handed pulling. This has important ergonomic implications; doubling the load approximately tripled the muscle activity, suggesting that the risk of overexertion to the anterior deltoid increases dramatically with load during these two techniques (Figure 27). No differences existed during two-handed pulling because the anterior deltoid is not functionally instrumental in performing this technique, resulting in low activation levels regardless of the load being moved. Load was only found to have a significant impact on muscle activity of the medial deltoid during pushing, where the heavier load resulted in an increase in muscle activity of 151%, augmenting

the risk of injury in the medial deltoid. Muscle activity of the posterior deltoid was affected by load in all three push/pull techniques, with the highest increase being observed for two-handed pulling (74%) when the load was doubled. This suggests that with increments in load mass, the difference between the muscle activity for one-handed pulling, found to elicit the highest results, and two-handed pulling is reduced.

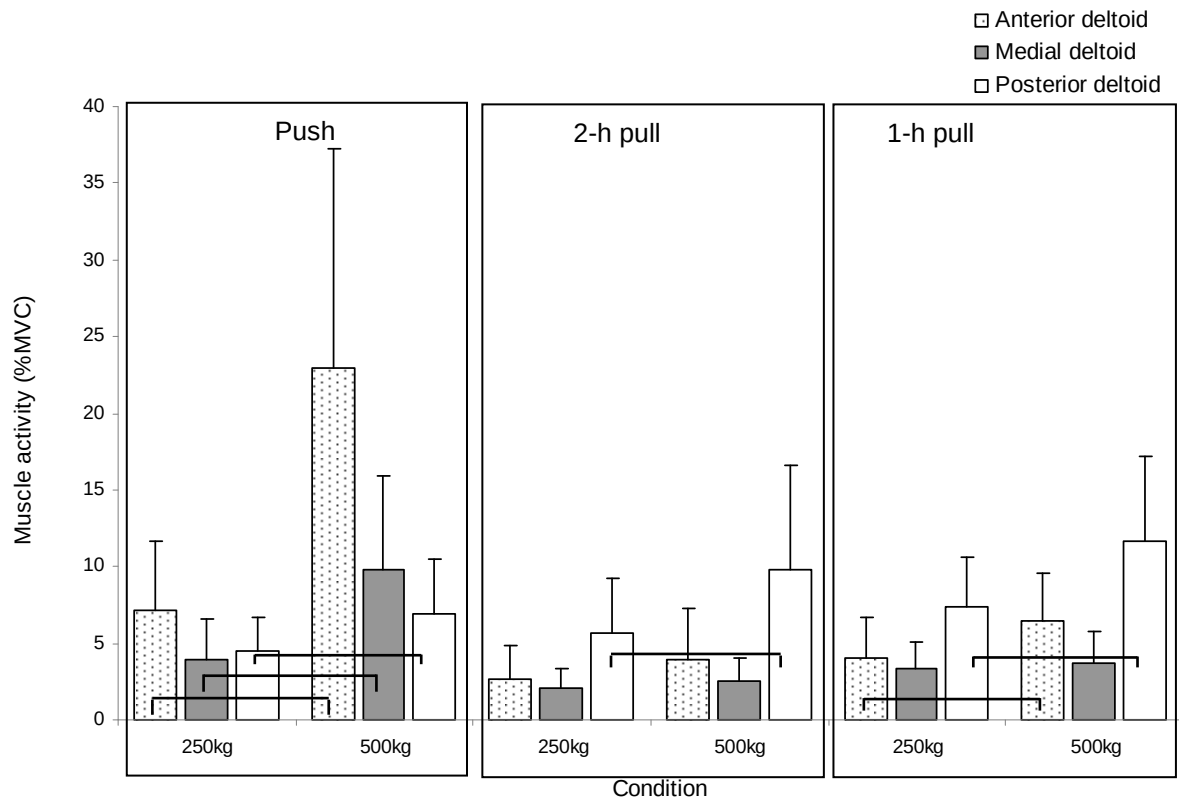


Figure 27. Muscle activity of deltoid muscles

Denotes statistical difference ($p < 0.05$)

BACK MUSCLES

Impact of technique

Technique and load affected muscle activity significantly in all three back muscles under investigation, although their effect was only interactive for trapezius. In general, there were statistical differences between all three techniques, with one-handed pulling being related to the greatest muscle activity (mean for both loads 11.20%MVC) for trapezius and two-handed pulling, the lowest (mean for both loads 2.81%MVC). The same differences were observed at each load; one-handed pulling elicited the highest muscular strain (9.58%MVC and 12.82%MVC

for 250kg and 500kg respectively) and two-handed pulling the lowest (2.59%MVC and 3.02%MVC for 250kg and 500kg respectively), seen in Table XXV.

Table XXV. Muscle activity of back muscles (% of MVC)

	<i>Load</i>		<i>Push</i>	<i>2-handed pull</i>	<i>1-handed pull</i>
Trapezius	250	Mean	3.59	2.59	9.58
		SD	2.10	2.20	4.79
	500	Mean	7.75	3.02	12.82
		SD	3.18	2.05	7.02
Latissimus dorsi	250	Mean	3.89	4.48	6.19
		SD	1.73	2.46	2.24
	500	Mean	6.14	7.76	10.93
		SD	2.88	5.95	4.86
Erector spinae	250	Mean	13.49	16.17	13.33
		SD	6.43	6.93	5.00
	500	Mean	17.79	21.47	15.01
		SD	6.60	8.92	6.08

┌─┐ Denotes statistical difference (p<0.05)
SD=standard deviation

Like trapezius, latissimus dorsi muscle activity was highest during one-handed pulling (mean for both loads 8.56%MVC), producing significantly higher responses than the other two techniques. Similar differences occurred at each load; with one-handed pulling responses being 48% and 57% higher than those of the bilateral conditions, for 250kg and 500kg respectively. Pushing and two-handed pulling produced statistically similar muscle responses, averaging 4.19%MVC (at 250kg) and 6.95%MVC (at 500kg).

Erector spinae was found to be most active during two-handed pulling (mean for both loads 18.82%MVC), eliciting a statistically higher response than one-handed pulling (mean for both loads 14.17%MVC), but responses for both these techniques were statistically similar to those related to pushing. At each load however, no significant differences were evidenced between techniques. Despite this, it is important to acknowledge that erector spinae muscle activity was consistently high, implying that by their very natures, pushing and pulling evoke high activation levels in this muscle.

Impact of load

Generally, significantly higher muscle activity was evidenced in all three back muscles at 500kg, compared to at 250kg, aggregated for all three techniques. Pushing at 500kg produced 116% higher muscle activity than at 250kg for trapezius, while for two-handed and one-handed pulling, muscle activity was unaffected (Figure 28). Considering latissimus dorsi, the higher load was associated with an increase of 58%, 73% and 77% for pushing, two-handed pulling and one-handed pulling respectively. This suggests that an increased load greatly affects latissimus dorsi muscle activity during both pulling techniques. Although muscle activity of erector spinae was higher at the heavier load (aggregated for all three techniques), no statistical differences existed between loads for each individual technique.

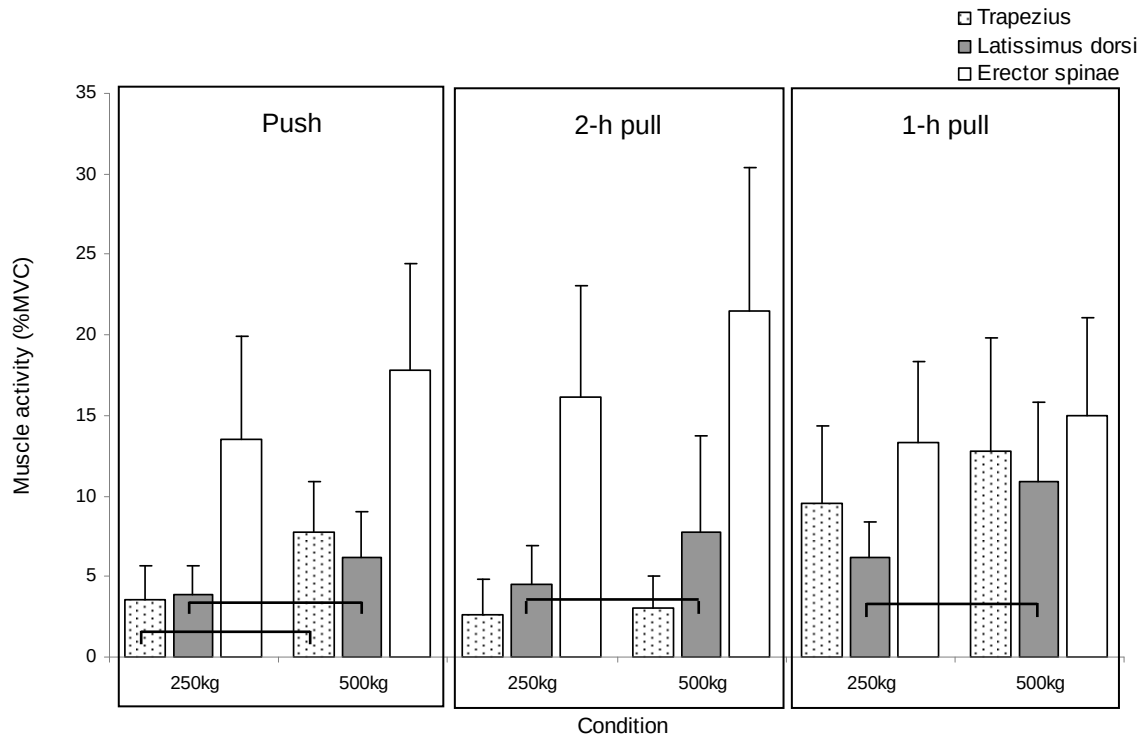


Figure 28. Muscle activity of back muscles

— Denotes statistical difference ($p < 0.05$)

BODY DISCOMFORT

Since perceptual ratings are associated with the intensity of the task (Gamberale, 1985), the use of body discomfort ratings were included. For the purposes of this study, generally only the body regions rated numerous times were included for assessment (Table XXVI). With respect to pushing at 250kg, only one individual indicated having experienced discomfort in any body region. These areas were in the posterior aspect of the body and included the forearms, middle back and calves, with intensity ratings of 2 or less, implying minimal strain. On the other hand, at 500kg, more individuals perceived discomfort. The areas most frequently rated anteriorly were the forearms, biceps brachii, quadriceps and tibialis anterior, while posteriorly the lower back and calves were identified. All areas except the quadriceps and tibialis anterior were associated with 3 or more frequency ratings (at intensities above 2.5), suggesting that more individuals perceived the task demands to increase with increments in load. Interestingly, the calves were most frequently rated during pushing at 500kg, implying that the lower extremities may

contribute greatly to pushing efforts, and are possibly at risk of overexertion, perhaps highlighting an area for future studies to explore.

Table XXVI. Perceptual ratings of body discomfort, indicating frequency of ratings and mean intensity of discomfort, in brackets

	<i>Push</i>		<i>2-handed pull</i>		<i>1-handed pull</i>	
	<i>250kg</i>	<i>500kg</i>	<i>250kg</i>	<i>500kg</i>	<i>250kg</i>	<i>500kg</i>
Hands				2 (4.0)		4 (3.2)
Forearms		5 (3.4)			7 (2.7)	10 (2.6)
Posterior forearms	1 (2.0)					
Biceps brachii		4 (2.8)		2 (3.5)	2 (2.5)	
Triceps brachii						5 (3.0)
Anterior deltoid						4 (2.5)
Posterior deltoid				2 (3.0)		
Upper back				2 (1.5)		
Middle back	1 (1.0)					
Lower back		3 (5.0)	3 (2.0)	4 (3.5)		3 (3.3)
Quadriceps		2 (1.5)				
Tibialis anterior		2 (1.5)				
Calves	1 (2.0)	9 (3.1)	5 (2.6)	10 (3.0)		3 (2.3)

During two-handed pulling at 250kg, the areas most frequently cited as feeling discomfort were the calves and lower back, receiving 5 and 3 ratings respectively. Both intensity ratings were below 3, indicating that discomfort was minimal. Doubling the load to 500kg, once again elicited a higher prevalence of ratings, and in general, the associated discomfort was greater (primarily over 3) compared to at the lower load. Similar to pushing, the calves were rated frequently (by 10 individuals) during two-handed pulling at 500kg, with an average intensity of 3. The high occurrence of ratings associated with the calves reiterates that the lower limbs are of concern during pushing and pulling activities, necessitating further investigation. Receiving 4 ratings at an intensity of 3.5, the lower back was perceived to experience light to moderate discomfort, while other areas also receiving multiple ratings included the hands, biceps brachii, posterior deltoid and upper back.

Discomfort was primarily felt on the right side of the body during one-handed pulling as this was the side 'driving' the effort. For the lighter load, the area that

incurred the most discomfort was the right forearm (rated by 7 individuals), with an average intensity rating of 2.7, associated with very little discomfort. At this load, the right biceps brachii also received multiple ratings with an average intensity of 2.5. With an increment in load mass to 500kg, the right hand, forearm and anterior deltoid were most often cited as feeling discomfort in the anterior aspect of the body, receiving intensity ratings ranging between 2.5 and 3.2, associated with light to moderate work. Of concern was the high frequency of ratings associated with the forearms at this load (rated by 10 individuals), suggesting that this small muscle endures high perceived strain. In the posterior aspect, the triceps, lower back and right calf experienced discomfort, with the highest intensity rating being 3.3 for the lower back.

CONCLUSION

Results have demonstrated that hand forces, spinal kinematic characteristics, muscle activity and perceptual ratings of discomfort are affected differently when the push/pull technique and/or load are altered, with some being influenced by technique, others by load and some by an interaction of the two. Within the present study, although biomechanical variables were primarily of concern, the results derived from the hand forces, spinal kinematic characteristics and muscle activity are not necessarily always in accordance. Furthermore, within each variable of interest, results may not be conclusive. This suggests that no one technique is optimal in every situation, and that provision of an ideal technique is dictated by the variables under consideration.

CHAPTER V

DISCUSSION

INTRODUCTION

The science of Ergonomics aims to minimise the hazards associated with the work setting, without compromising productivity. In this light, the risks of dynamic pushing and pulling, common occurrences in industry, have been investigated with particular emphasis on the hand forces exerted, as they are reported to have a direct association with spinal loading (Jansen **et al.**, 2002), which is usually derived from estimates using biomechanical models (such as Lee **et al.**, 1991). Although trunk motion has been related to spinal loading (Davis and Marras, 2000), this variable has not been substantially related to pushing/pulling activities, rendering the body of literature inadequate. Furthermore, some studies have been concerned with muscle activity during the performance of these tasks, focusing primarily on the trunk musculature, whereas the peripheral body has largely been ignored. Under various combinations of push/pull technique and load, hand forces, spinal kinematic characteristics, upper body muscle activity and perceptual ratings of body discomfort were measured to determine the impact of these independent variables on the musculoskeletal system.

HAND FORCE EXERTION

In accordance with numerous authors (Resnick and Chaffin, 1995; Donders **et al.**, 1997; van der Beek **et al.**, 1999; van der Beek **et al.**, 2000; Jansen **et al.**, 2002; Cripwell, 2007; Bennett **et al.**, 2008), findings indicated that the higher the load mass to be moved, the higher the hand forces exerted. Some have even elucidated that this relationship is linear, with strong correlations of over 0.8 being reported (such as Resnick and Chaffin, 1995; Donders **et al.**, 1997; van der Beek **et al.**, 2000; Bennett **et al.**, 2008). This suggests that forces attained in moving loads other than those studied can be estimated using regression equations. However, these are unique to each situation. Figure 29 depicts the findings of various studies, describing the linearity and correlations of the load mass and initial hand force relationship for pushing, while concurrently highlighting

discrepancies between estimates of force output (at the same load) between studies.

According to this figure, estimates of force exertion at the same loads are explicitly dissimilar when four different regression equations are applied. For example at 250kg, predicted forces range from the lowest of approximately 75N to the highest of 325N. In the current study, the mean force for pushing at the same load was 198N. The difference in results highlights the importance of considering variation between experimental conditions, together with contextual factors, such as wheel/floor friction. This means that the ergonomist who strives to maintain tasks within a safety margin must acknowledge that no two contexts are identical in terms of environmental, task, design and operator factors. Applying regression equations to contexts other than those from which they were developed must thus be done cautiously.

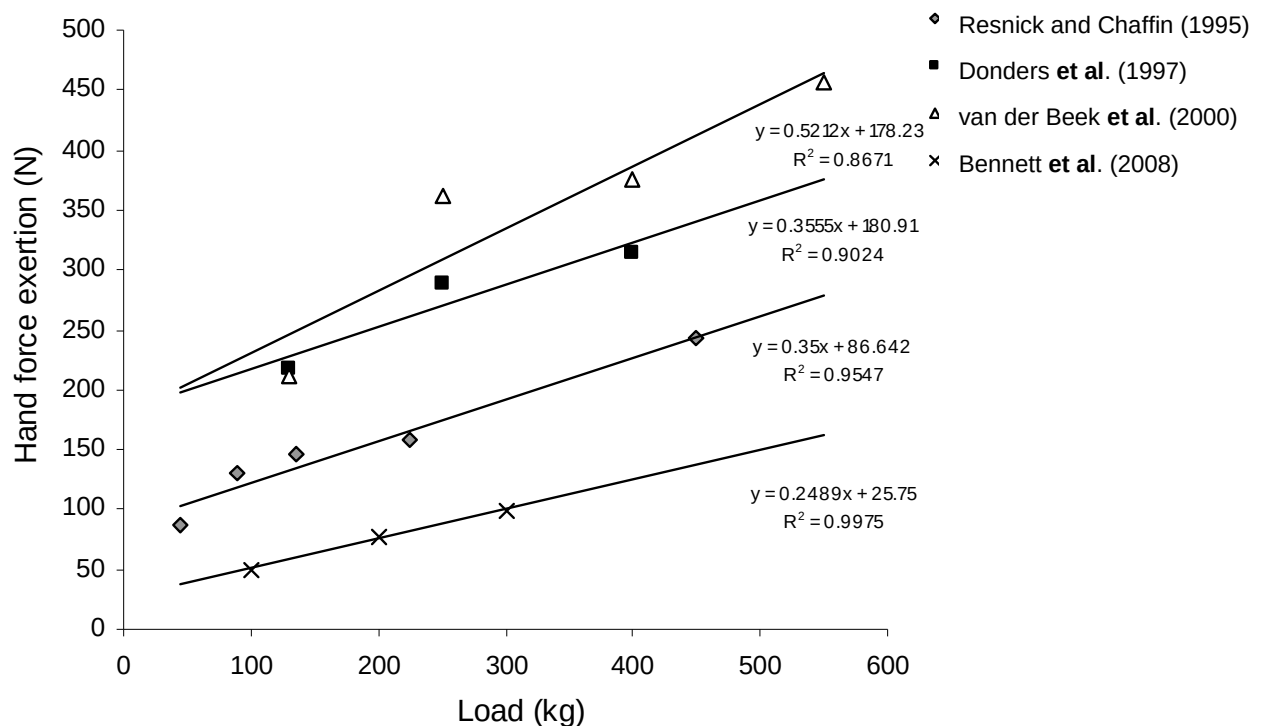


Figure 29. Inter-study differences in linear load-force relationship (Resnick and Chaffin, 1995; Donders et al., 1997; van der Beek et al., 2000; Bennett et al., 2008)

A conclusion established from the current research (Figures 12, 13 and 14), is that not only is the linear relationship context-specific, but that it is also unique to each motion phase. Despite the consistent increase in load mass from 250kg to 500kg, increments in hand forces were not uniform across the motion phases. During the initial and ending phases, forces increased by, on average, 64% and 58% respectively, while in the sustained phase, the increase was much more pronounced at 145%. Present results were compared with those derived from the study by van der Beek **et al.** (2000), whose male sample group displayed similar anthropometric characteristics to the individuals in the current investigation. Accordingly, the largest increase in force due to load occurred during the sustained phase, a result which is consistent between the two investigations. However, the increments were greater in the present study and can perhaps be attributed to methodological differences between the two studies. These may be related to factors such as handle height or walking speed. Van der Beek **et al.** (2000) afforded participants the opportunity to select handle height based on individual comfort, while the present study imposed restrictions on this variable, indicating that perhaps posture adopted or direction of hand forces as a consequence of handle height varied between studies, resulting in differences in force production. The speed of walking also varied between the studies and may have affected the magnitude of hand force output. Nonetheless, both studies have demonstrated more pronounced increments in sustained hand forces, emphasising that although this phase of motion is not usually deemed to contribute greatly to the task demands, it occurs over longer periods than the initial or ending phases and requires the exertion of submaximal forces for prolonged periods, all of which increase with higher loads.

Hand Force Exertion Relative to Body Mass

Although body mass was uncontrolled, in attaining forces of similar magnitude, individuals of higher body mass (particularly lean body mass) would more easily achieve them, and therefore be at a lower risk of exceeding their physical capacities. This necessitated expressing force output as a percentage relative to body mass (in Newtons), shown in Table XXVII. As they relate to the hand forces,

it was expected that the highest demand would be associated with the initial phase of each exertion. Here, the requisite forces exerted corresponded to individuals producing, on average, 24% and 40% of body mass for 250kg and 500kg respectively. In contrast, the least physical stress was evident in the sustained forces. At the lower load (250kg), individuals were exerting less than 7% of body mass across all techniques, which more than doubled with the increase in load mass to 500kg. While the demands imposed on the human body during the ending phase were higher than during the sustained phase for the same loads, the lowest demand, corresponding to the lowest load in the ending phase, equalled the highest demand in the sustained phase, associated with the highest load. The magnitudes for these demands were, on average, 14% of body mass. Although the sustained forces are typically considered to evoke the lowest strain in the human operator, these findings must be acknowledged and the premise that workers will be required to exert close to 15% of body mass for prolonged periods over an eight hour work shift must be considered. The high exertions of the initial and ending phases, coupled with the submaximal extended exertions of the sustained phase may lead to debilitating injuries in the future.

Table XXVII. Requisite forces as a percent of body mass, in Newtons

		<i>Push</i>		<i>2-handed pull</i>		<i>1-handed pull</i>	
		<i>250kg</i>	<i>500kg</i>	<i>250kg</i>	<i>500kg</i>	<i>250kg</i>	<i>500kg</i>
Initial	Mean peak force (N)	198.36	327.23	191.78	303.17	173.44	294.22
	% of body mass	25.79	42.54	24.93	39.41	22.55	38.25
Sustained	Mean force (N)	46.45	111.28	42.69	102.80	40.80	103.43
	% of body mass	6.04	14.47	5.55	13.36	5.30	13.45
Ending	Mean peak force (N)	-103.97	-159.54	-98.63	-160.86	-113.32	-178.31
	% of body mass	13.52	20.74	12.82	20.91	14.73	23.18

 Indicates conditions under which more than 30% of body mass was exerted

 Indicates conditions under which 20-30% of body mass was exerted

 Indicates conditions under which 10-20% of body mass was exerted

Comparison with Existing Acceptable Limits

Under the supposition that hand forces are possible indicators of the strain evoked in the human body (Lee **et al.**, 1991; Hoozemans **et al.**, 1998; van der Beek **et al.**,

1999), and therefore an index of the risk of injury, guidelines exist outlining maximum acceptable hand forces that should not be surpassed in order to enhance protection of the worker. Some of the most widely implemented parameters have been developed by Eastman Kodak (1986), Snook and Ciriello (1991) and the HSE (1998). Yet, they are not without their limitations. Those proposed by Eastman Kodak (1986) and the HSE (1998) negate mentioning contextual factors such as distance moved or frequency of exertion. Conversely, those outlined by Snook and Ciriello (1991) are more comprehensive and present psychophysical recommendations of maximum forces considered acceptable to different percentiles of the male and female industrial population. They are based on distance, frequency, height of force application, type of exertion and apply to the initial and sustained motion phases, but do not provide recommendations for ending forces. These authors cautioned that some of the data provided was not scientifically validated, but rather based on assumptions. Furthermore, Ciriello **et al.** (2008) opined that secular changes occur in the maximum acceptable forces related to pushing and pulling. They reported that the maximum acceptable initial and sustained forces for male industrial workers was reduced over a 20 year period, and currently average 94% and 83% respectively of the original values, suggesting that recommendations may become less applicable over extended periods. Although this implies that guidelines must be applied tentatively, they do provide some direction as to what forces are considered acceptable during pushing and pulling tasks and contribute to furthering the body of science in this area.

Figure 30 illustrates the initial hand forces derived from the present study in comparison with existing guidelines. The most conservative limit, proposed by Eastman Kodak and Snook and Ciriello (1991) (based on the 90th percentile male) is approximately 225N, while the highest is 245N (HSE, 1998). Using these as reference points, the initial forces exerted at 250kg, regardless of the push/pull technique, were within acceptable limits, falling at least 26N below the most conservative recommendation. In contrast, the initial forces at 500kg were considered unacceptable across all techniques, being at least 49N greater than the highest recommended acceptable limit. In congruence with Jung **et al.** (2005),

these findings indicate that load mass moved is a key factor in determining hand force exertion during pushing and pulling. As such, load mass directly influences the acceptability of exerted hand forces.

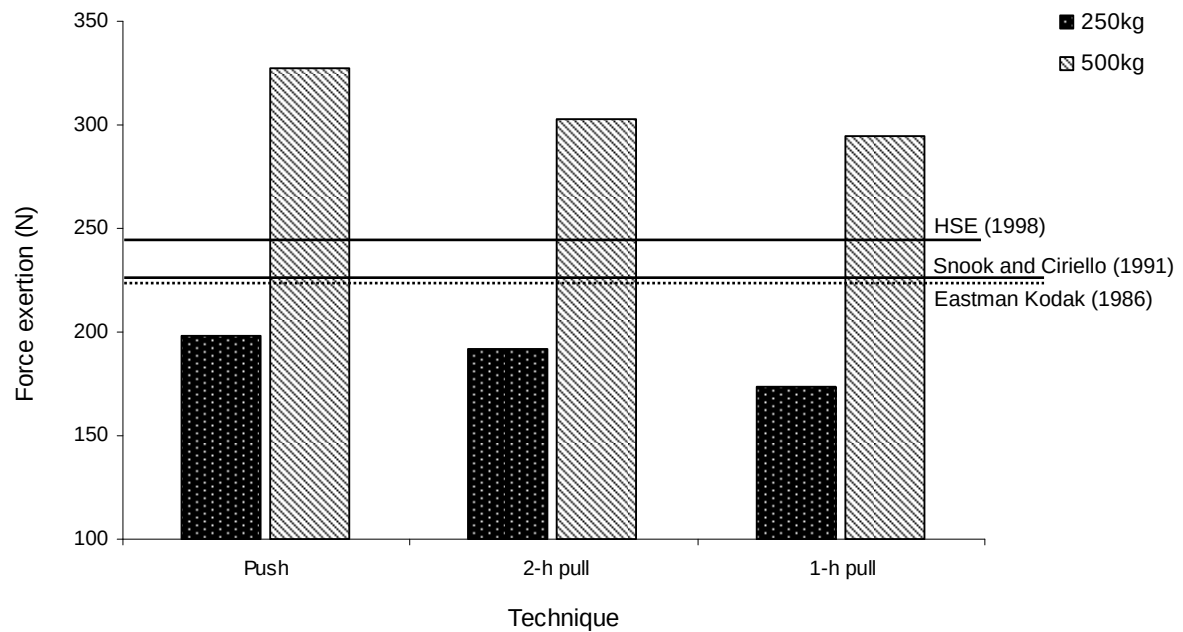


Figure 30. Comparison of initial forces to existing guidelines for acceptable limits

Recommendations for sustained forces were at least 95N lower than those of the initial phase, ranging between 98N and 130N. According to Figure 31, sustained forces at 250kg, independent of technique, were maintained within acceptable limits, whereas those exhibited at 500kg were much less conclusive. Using the guidelines by Eastman Kodak (1986) and Snook and Ciriello (1991), the lowest of which was 112N, sustained forces were considered to be acceptable, but according to the HSE (1998), the sustained forces violated recommendations by approximately 10N. It must be acknowledged that over an eight hour shift, it is doubtful that loads in excess of 500kg could be moved without undue fatigue and therefore an increase in load would inevitably be detrimental to health.

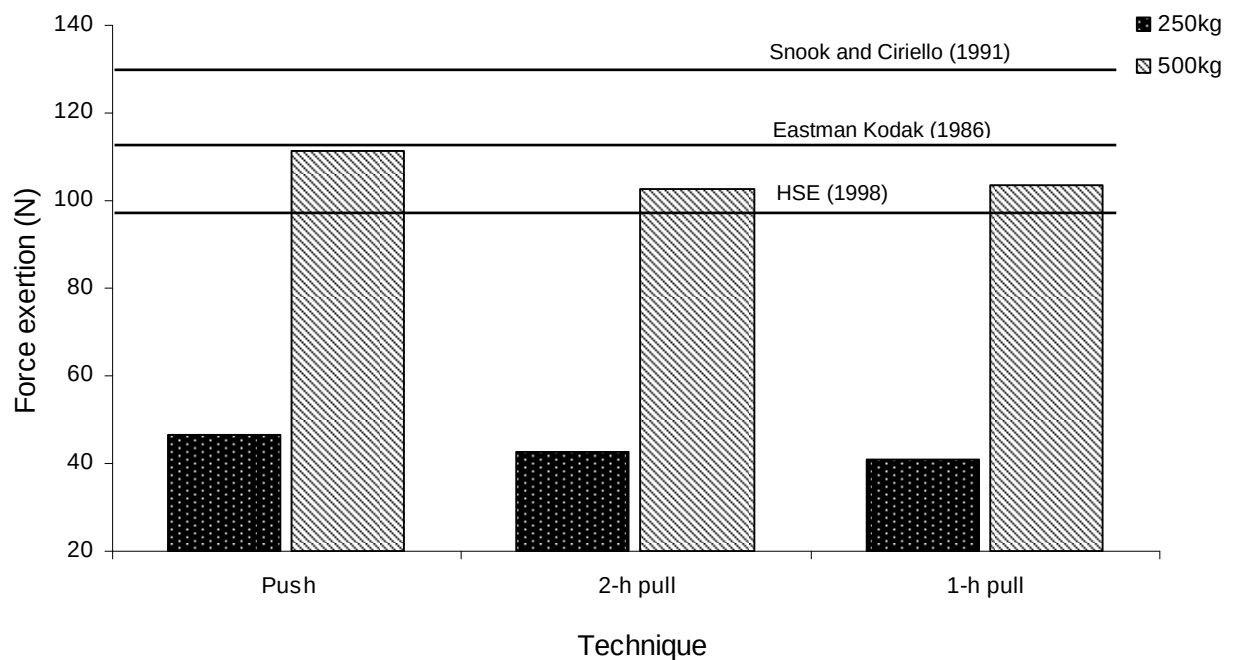


Figure 31. Comparison of sustained forces to existing guidelines for acceptable limits

Ending forces, like those evidenced in the initial phase are characterised by a distinct peak in force production, but parameters for acceptability of forces are less widely available. Those by Eastman Kodak (1986) refer only to emergency stopping (360N) and not to a gradual deceleration. It was therefore expected that ending forces would be maintained within acceptable limits, as was the case (Figure 32). Similarly, all ending forces, regardless of technique and load did not exceed the recommendation proposed by the HSE of 245N. Based on these margins of acceptability, it appears that the ending forces place individuals at the least risk of overexertion. However, given that few guidelines are available for comparison, this finding should be accepted with due caution.

Due to the linear relationship between load mass and force exertion (Resnick and Chaffin, 1995; Donders *et al.*, 1997; Jung *et al.*, 2005; Todd, 2005; Cripwell, 2007; Bennett *et al.*, 2008), load is inevitably a strong determinant of the acceptability of the magnitude of hand forces. Thus in accordance with previous recommendations, (Lawson *et al.*, 1993; Resnick and Chaffin, 1995; van der Beek *et al.*, 2000; Hoozemans *et al.*, 2004), regardless of other contextual factors

(although they should not be neglected), load mass should be minimised wherever possible.

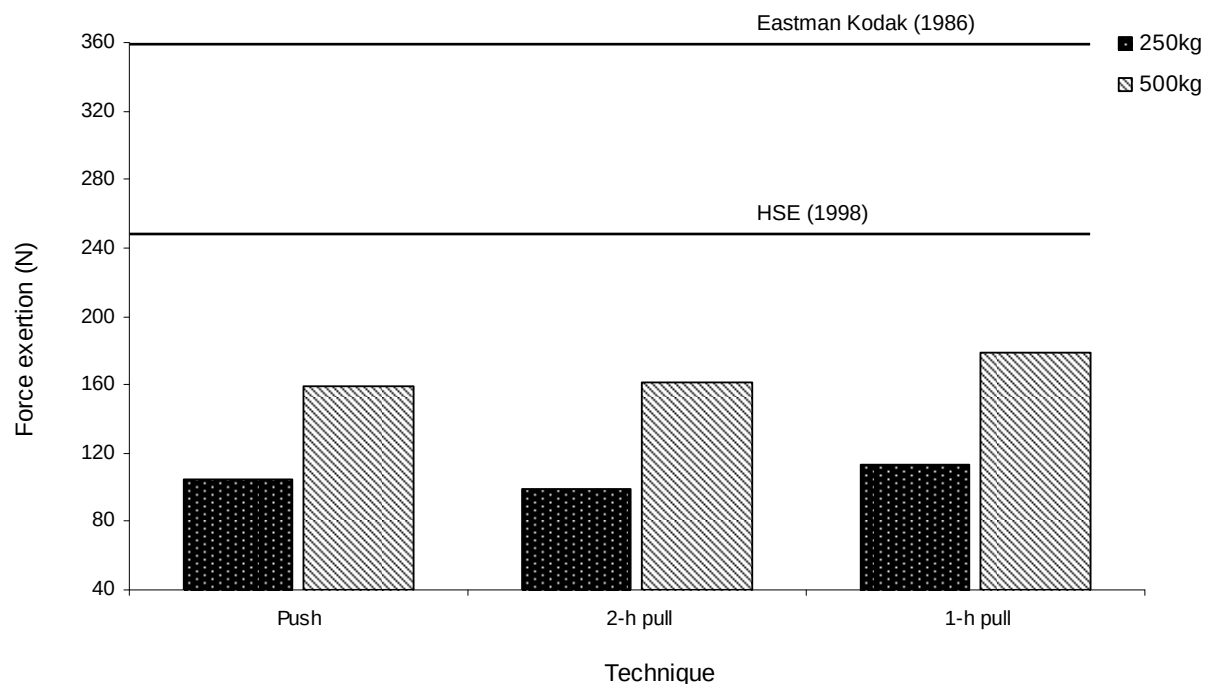


Figure 32. Comparison of ending forces to existing guidelines for acceptable limits

Contextual challenges are encountered when comparing guidelines and literature, given that they differ with respect to methodological protocols and environmental factors. For example, Daams (1993) opined that estimating forces derived under constrained postures have low predictive ability to tasks performed under freely chosen postures. This suggests that recommendations are most applicable to populations and contexts similar to those investigated and lack general applicability.

Guidelines based on hand force exertion, although extensively employed, must be applied tentatively. Based on research by Hoozemans **et al.** (2004), the use of hand forces as an indicator of load at the lower back and shoulder girdle is not necessarily substantiated. These authors have argued that better indices of risk may be direction of motion (van der Beek **et al.**, 1999; de Looze **et al.**, 2000), posture and movement (Hoozemans **et al.**, 2004). Yet they cautioned that higher forces than those evidenced in their study (corresponding to loads over 320kg)

may indeed relatively affect stresses imposed on these body regions, possibly an area requiring further research. Similarly, Hoozemans **et al.** (2007) suggested that in addition to the magnitude and direction of hand forces, the posture of the trunk and its deviation from the vertical upright stance may be important determinants of lower back loading. Taking cognisance of these factors, this study investigated lumbar segment movement that occurs with different pushing and pulling techniques, using measures of spinal kinematics. In this way, posture and movement elements were assessed, providing some insight into the movement implications of pushing and pulling.

SPINAL KINEMATICS

Spinal kinematics has been advocated as being instrumental in the development of lower back disorders (Davis and Marras, 2000). Yet, in relation to pushing and pulling, it has been under-appreciated as a potential risk factor, and therefore comparative literature is largely unattainable. In all trunk motion factors under investigation, with the exception of mean position in all planes, coefficients of variation were between 19% and 38%. They were however generally higher for mean positions, with all being at least 32%, implying that spinal kinematic measures are highly changeable between individuals performing the same pushing/pulling task. Although not in accordance with Allread **et al.** (2000) who opined that these variables are mostly determined by workplace and job design as opposed to individuals performing the same job, the tasks sampled in their study did not specifically relate to pushing and pulling, but rather only to repetitive tasks that involved some form of MMH work. Perhaps this suggests that measures of spinal kinematics and in particular, spinal position are variable between individuals for the same pushing/pulling tasks.

Lower Back Disorder Risk of Pushing and Pulling

Table XXVIII shows the risk of developing a LBD associated with each experimental condition, using the guidelines provided by Marras **et al.** (1995), according to lumbar segment displacements, velocities and accelerations. With reference to maximum ranges, pushing and two-handed pulling responses in all three cardinal planes were found to be associated with low risk activities. These

findings seem to support the argument that loads can be moved with less musculoskeletal strain during pushing and pulling as opposed to lifting. Given that two-handed pulling tended to be associated with the highest sagittal flexion and ranges of motion at 500kg, it was expected that this technique would place individuals at a higher risk of developing LBDs. Yet, even at 500kg, it is classified as a low risk activity with regard to sagittal range. In respect of one-handed pulling, maximum sagittal and lateral ranges were similar to the bilateral techniques and related to low risk activities, irrespective of the load moved. However, at both loads, one-handed pulling ROMs in the transverse plane (35.27° and 37.73° for 250kg and 500kg respectively) were statistically higher than for the other two techniques and were classified as being high risk, exceeding the limit of 21.28° .

Considering maximum velocities, once again, two-handed pulling responses in all planes were considered low risk. Comparatively, maximum pushing velocities in the transverse plane ($39.18^{\circ}.\text{s}^{-1}$ and $43.98^{\circ}.\text{s}^{-1}$ for 250kg and 500kg respectively) categorised this activity as imposing a moderate risk. Similar to the transverse ranges, one-handed pulling elicited significantly higher transverse velocities than the other techniques at both loads, and was at least $8^{\circ}.\text{s}^{-1}$ greater than the $49.72^{\circ}.\text{s}^{-1}$ proposed value, associating it with high risk. Although previous research has identified that one-handed pulling is associated with twisting, few studies have attempted to quantify this.

In terms of maximum accelerations, those associated with two-handed pulling, similar to the maximum ranges and velocities, were classified as being low risk in all movement planes. Within the sagittal and lateral planes, pushing accelerations were low risk, but in the transverse plane, maximum accelerations, found to be statistically higher than two-handed pulling responses, were categorised as medium and high risk at 250kg and 500kg respectively. While sagittal accelerations at both loads and lateral accelerations at 250kg related to one-handed pulling imposed a low risk on individuals, at 500kg, lateral acceleration for this technique was medium risk. In the transverse plane, maximum acceleration for one-handed pulling, found to be statistically higher than those for the other

techniques at both loads, exceeded the limit of $320.91^{\circ} \cdot s^{-2}$, and hence, was related to a high risk.

Table XXVIII. Spinal kinematics in relation to recommendations by Marras **et al.** (1995)

Maximum Range ($^{\circ}$)	Load (kg)	Push	2-handed pull	1-handed pull
Sagittal	250	9.43	12.59	12.64
	500	13.19	17.96	15.93
Lateral	250	9.13	8.31	14.81
	500	11.18	9.28	19.42
Transverse	250	17.06	13.34	35.27
	500	20.17	14.53	37.73
Maximum Velocity ($^{\circ} \cdot s^{-1}$)	Load (kg)	Push	2-handed pull	1-handed pull
Sagittal	250	17.05	20.85	20.54
	500	23.16	25.14	25.86
Lateral	250	25.30	21.33	29.07
	500	28.35	20.96	33.12
Transverse	250	39.18	30.58	58.14
	500	43.98	30.12	57.85
Maximum Acceleration ($^{\circ} \cdot s^{-2}$)	Load (kg)	Push	2-handed pull	1-handed pull
Sagittal	250	125.89	162.46	141.34
	500	175.40	177.99	187.17
Lateral	250	193.78	172.44	218.88
	500	206.07	163.54	245.19
Transverse	250	297.21	239.80	362.20
	500	322.14	221.61	393.84

Indicates high risk activity
 Indicates medium risk activity
 Indicates low risk activity

Based on the classification system, despite the highest sagittal displacements being associated with two-handed pulling, all measures were within low risk parameters, classifying the overall risk as low. Pushing, although low risk for all sagittal and lateral measures, was medium to high risk with respect to transverse velocity and acceleration. Evidently, the asymmetrical nature of one-handed pulling, associated with substantial transverse movement between the vertebrae

and thus increased shear and compressive forces (Davis and Marras, 2000), identifies this technique as a high risk activity, with respect to spinal kinematic variables in the transverse plane. Based on the incidence of variables being classified as high risk for each technique, the highest risk occurred for one-handed pulling, followed by pushing. Conclusively, one-handed pulling should be avoided where possible, while two-handed pulling appears to be preferable.

Low Back Disorder Risk Model

The Low Back Disorder Risk Model, developed by Marras **et al.** (1993) makes use of a combination of two task (maximum moment and frequency) and three spinal motion factors (maximum sagittal flexion, maximum lateral velocity and average twisting velocity) to distinguish between activities that place individuals at high and low risk of developing LBDs. The multivariate nature of this model deems it to be a highly useful and applicable tool. Employing this model, the probability of risk for each technique using both loads was calculated for an eight hour work shift (as shown in Figure 33), based on the premise that workers in industry are likely to perform for an eight hour work shift.

With the exception of two-handed pulling at 250kg, all techniques, independent of load, corresponded to more than a 50% probability of high risk group membership. Although statistical significance cannot be determined, the probabilities were lowest for two-handed pulling (49% for 250kg and 51% for 500kg) and highest for one-handed pulling (58% and 64% for 250kg and 500kg respectively), findings which are congruent with the classifications proposed by Marras **et al.** (1995), shown in Table XXVIII. Even at the lower load of 250kg, the risk related to one-handed pulling either equalled or surpassed the risk related to pushing or two-handed pulling at the higher load, reiterating the role that technique plays in the determining the probability of exposure to LBDs.

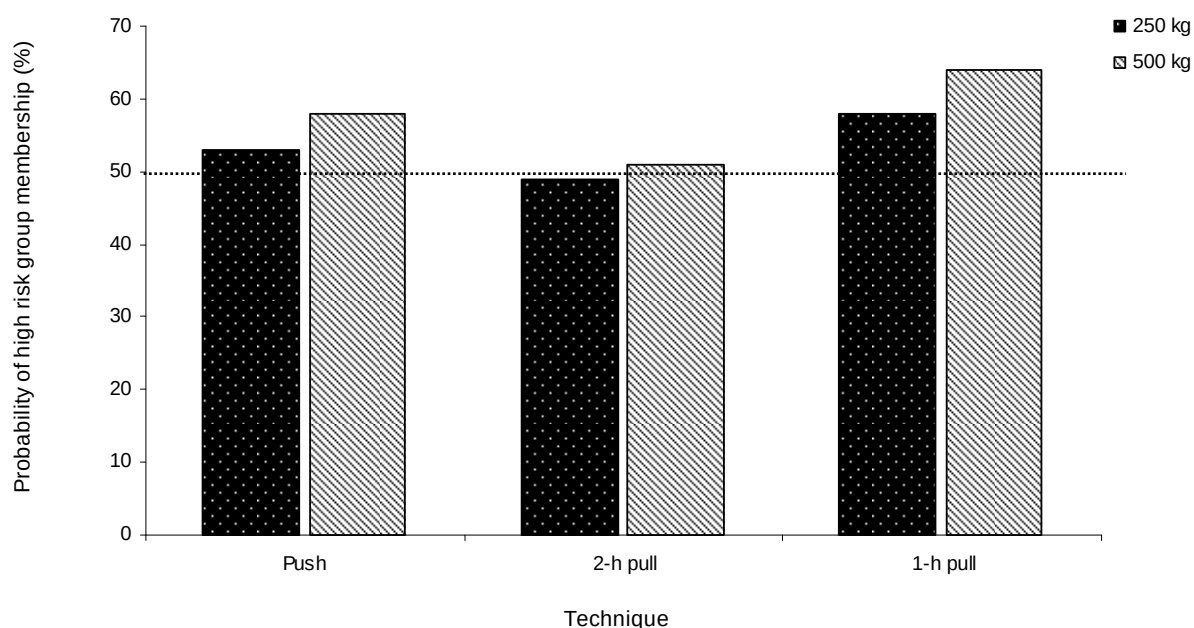


Figure 33. Probability of high risk group membership for lower back disorders

Although this model acknowledges the role that motion as well as critical task factors play in the proliferation of LBDs, establishing it as an invaluable tool, it must not be neglected that pushing and pulling tasks are frequently related to slip, trip and fall accidents, which account for approximately 13% of back injuries (Manning *et al.*, 1984). Models that are not only able to predict the risks inherent in the activity, but that are also able to predict the risk of slip, trip and falls based on postures and other task characteristics would prove to be highly useful in further understanding the hazards related to push/pull activities.

Joint Loading at L₅/S₁

Although caution must be taken when using static models to estimate dynamic joint loading, initiating movement of the pallet jack can be approximated to a static task. Photographs were uploaded to a software programme, ErgoImager™ (NexGen Ergonomics, Inc.), which interfaces with the University of Michigan's Three Dimensional Static Strength Prediction Programme, to be analysed. This allowed L₅/S₁ compression and shear in the sagittal plane to be estimated as movement was initiated (Table XXIX). This predicted the load imposed on the lower back at arguably the most stressful phase of motion, where inertia and wheel/floor frictional properties are highest.

Pushing or pulling the heavier load, irrespective of the technique adopted resulted in higher deviations of the body, and particularly the trunk from the 'normal' upright bipedal stance compared to the postures assumed when moving the lighter load. In the upright stance, the forces acting on the spine are generally compressive, and any deviations from it tend to accentuate loading at the lumbosacral joint. The stresses incurred as a consequence of more extreme postures being adopted will thus be elevated. Comparing the postures assumed for the same techniques across loads, it is apparent that the use of body mass to initiate movement causes more forward leaning during pushing, greater degrees of trunk flexion during two-handed pulling and more pronounced lateral bending during one-handed pulling, all of which are expected to elicit greater strain in the human operator.

Table XXIX. Compressive and shear forces acting on L₅/S₁ as a result of postures adopted when initiating movement

	250kg		500kg	
	<i>Push</i>		<i>Push</i>	
Compression (N)	1222		2824	
Shear force (N)	356		274	
	<i>2-h pull</i>		<i>2-h pull</i>	
Compression (N)	2991		3588	
Shear force (N)	333		297	
	<i>1-h pull</i>		<i>1-h pull</i>	
Compression (N)	1189		1233	
Shear force (N)	360		353	

Corresponding to the postures, increases in the load moved were accompanied by increments in spinal loading, particularly due to compressive forces, across all techniques. In accordance with spinal kinematic responses, the greatest degree of

flexion and highest sagittal ranges were evidenced during two-handed pulling. Thus it was expected that two-handed pulling would correspond to the highest compressive forces experienced at L₅/S₁; 2991N and 3588N for 250kg and 500kg respectively. This finding has been confirmed by previous studies. (Lee **et al.**, 1991; de Looze **et al.**, 1995; de Looze **et al.**, 2000; Hoozemans **et al.**, 2004). During two-handed pulling the spine flexes, flattening the lumbar region, thereby contributing to an increased compression component, a finding reported Resnick and Chaffin (1995) and Granata **et al.** (2005). These authors associated bending at the torso with high compressive forces in the spine, which Granata **et al.** (2005) attributed to an enhanced muscular co-contraction during trunk flexion (Granata **et al.**, 2005). Although associated with the lowest overall spinal kinematic responses, and systematically being classified as a low risk activity according to the Low Back Disorder Model (Marras **et al.**, 1993), compression tended to be the highest during two-handed pulling and grossly contributes to spinal stresses at L₅/S₁.

Compressive forces estimated in this study were comparable to published findings. De Looze **et al.** (1995) reported peak values to be 1657N and 2654N for pushing and pulling respectively, while those reported by Laursen and Schibye (2002) were more conservative, between 600N to 1100N for pushing and one-handed pulling, regardless of the load moved. At a load of 225kg, Resnick and Chaffin (1995) estimated compression to be in excess of the NIOSH action limit of 3400N for pushing. In the present study, all forces were maintained below this value at the load of 250kg. Compressive forces as a result of pushing and one-handed pulling were approximately 35% of the recommended limit, while two-handed pulling was as high as 88%. When the load mass was doubled, compressive forces during pushing approximated those of two-handed pulling at 250kg, while one-handed pulling elicited comparatively lower values (1233N). The greatest compression, associated with two-handed pulling at 500kg, corresponded to the 3400N limit being violated by almost 200N. Conclusively, in terms of compression experienced at the lumbosacral joint, two-handed pulling is associated with the greatest stresses. Although compressive forces of 3400N place individuals of 40years and over at an elevated risk of vertebral end plate damage, the cumulative effect of performing these tasks, even in younger workers,

must not be negated. It is unlikely that workers who perform repetitive pushing and pulling tasks for eight hours a day, over a number of years, will not experience the ill-effects of cumulative damage to the musculoskeletal system.

Since vertebral tolerance to shear forces is lower than compression, the conditions eliciting high shear forces are likely to place individuals at an elevated risk of injuries to the lower back. Although shear forces were similar across techniques, at both loads they tended to highest during one-handed pulling (360N and 353N for 250kg and 500kg respectively). These findings are in accordance with the spinal kinematic responses, which identified one-handed pulling as typically evidencing the highest movements in the lateral and transverse planes. All shear forces were observed to be maintained within reported tolerance limits of 1735N (Farfan **et al.**, 1970), 1000N (McGill, 1997) and 2500N (Yingling **et al.**, 1999). However, it is inconclusive whether these values are considered acceptable since literature surrounding shear during pushing and pulling is limited. Compared to published findings, which estimate shear forces to be between 200N (Laursen and Schibye, 2002) and 800N (Hoozemans **et al.**, 2004) for push/pull tasks, the current values are within this range. Although the shear forces imposed on the lumbar spine seem to be within acceptable limits, similar to the compressive forces, the impact of cumulative stress must be afforded due acknowledgement.

MUSCLE ACTIVITY

Muscle Profile

Within the current study, the use of electromyography assisted in determining which muscles in the upper body were placed under the most stress, thus identifying the push/pull technique imposing the highest task demands on the muscle system. Although variability within conditions was high (with coefficients of variation of at least 18%), possibly due to individual differences in muscle geometry and subcutaneous tissue (Göbel, 2005), the results of this research have made it possible to develop a muscle profile (Table XXX) indicating the three most active muscles in the upper body during each push/pull technique, regardless of the load employed. Each technique was characterised by its own unique muscle profile which was consistent across loads, and within the vocational

milieu, means that not only can the technique imposing the highest muscular strain be avoided, but also that different push/pull techniques can be employed at various times throughout the day, preventing the same muscles from being taxed repetitively. Acknowledging that this would be wholly beneficial, cognisance must be taken of the fact that erector spinae, found to be highly activated under all conditions, is still likely to experience muscle strain. Together with knowledge of the muscles most likely to fatigue early, the muscle profile is seemingly applicable to industry.

Table XXX. Muscle profile for each push/pull technique, based on activation levels

	<i>Push</i>		<i>2-h pull</i>		<i>1-h pull</i>	
	<i>250kg</i>	<i>500kg</i>	<i>250kg</i>	<i>500kg</i>	<i>250kg</i>	<i>500kg</i>
	<i>Muscle Activation Levels (%MVC)</i>					
Brachioradialis	3.67	6.69	2.96	3.87	*9.65	*15.20
Triceps brachii	7.97	*10.81	8.82	*13.55	5.29	*11.35
Anterior deltoid	7.12	*22.96	2.70	3.88	4.06	6.48
Medial deltoid	3.90	*9.80	2.07	2.53	3.37	3.72
Posterior deltoid	4.50	6.97	5.67	*9.85	7.39	*11.63
Trapezius	3.59	7.75	2.59	3.02	*9.58	*12.82
Latissimus dorsi	3.89	6.14	4.48	7.76	6.19	*10.93
Erector spinae	*13.49	*17.79	*16.17	*21.47	*13.33	*15.01

Note: Shaded areas indicate the three muscles most highly activated during each technique

* Indicates the muscles exceeding the 10%MVC limit for the onset of fatigue (Redfern, 1992)

During pushing, the muscles found to elicit the highest muscle activation levels were the triceps brachii, the anterior deltoid and erector spinae. At the lower load, these muscles were found to be activated to between 7%MVC and 14%MVC, with the lowest activation levels of the three occurring in the anterior deltoid and the highest in erector spinae. However the degree of activation in the muscles increased with the increment in load from 250kg to 500kg, causing them to work at a higher percentage of their MVCs, and placing them at an elevated risk of experiencing strain. This is in agreement with Sogaard *et al.* (2001), who investigated mopping and scrubbing tasks, typically involving push/pull actions. According to these authors, movement of heavier loads corresponds to increased muscle activation levels compared to lower loads. The elevation in muscle activity

in the present study was however not uniform between muscles for the same technique. Doubling the load from 250kg to 500kg resulted in tripling the activation levels in the anterior deltoid, while increases of 36% in the triceps brachii and only 32% in erector spinae were seen. Although all three muscles are of concern at both loads, a greater effort is required from the anterior deltoid at the higher load. This is a key observation, and indicates that since this muscle is a comparatively smaller, more gracile muscle than erector spinae, working at these high levels is likely to result in the early onset of fatigue and decrements in performance. Although muscle activity in the medial deltoid and trapezius at least doubled at 500kg, values were still relatively low.

As in the case of pushing, the triceps brachii and erector spinae were among the most highly activated muscles during two-handed pulling. Although these techniques were typically related to the least mechanical stress, reflected in the spinal kinematic responses, they place high stresses on the muscle system, particularly at 500kg. In addition to these muscles, the posterior deltoid was also highly activated during two-handed pulling. At 250kg, the posterior deltoid was least active out of these three muscles, eliciting activation levels of 5.67%MVC, while erector spinae was most active (16.17%MVC). Once again, the increase in load caused substantial differences in the increase in activity for each muscle. These corresponded to 54%, 74% and 33% in the triceps brachii, posterior deltoid and erector spinae respectively. In accordance with the pushing responses, the highest increase was evidenced in a smaller muscle group, suggesting that any additional increases in load would lead to this muscle fatiguing rapidly. However, it must be noted that muscle activation levels in erector spinae (21.47%MVC) were still relatively higher than the other two muscles.

The highest activation levels during one-handed pulling occurred in brachioradialis, trapezius and erector spinae. At 250kg, activation levels of brachioradialis and trapezius averaged at 9.62%MVC and were lower than the responses for erector spinae (13.33%MVC). When the load increased to 500kg, brachioradialis was working at 15.20%MVC, corresponding to an increase of 1.5 times, the highest increase between the three muscles. Confirming the results for

pushing and two-handed pulling, it appears that when load mass increases, the smaller muscles evidence larger increments in muscle activity across techniques. When the load was doubled, muscle activation levels for the triceps brachii and latissimus dorsi were also of concern during one-handed pulling, increasing from 5.29%MVC to 11.35%MVC and 6.19%MVC to 10.93%MVC respectively.

Perhaps one of the most critical findings relating to muscle activity during various push/pull techniques, was that erector spinae was always highly activated for all conditions by at least 13%MVC, and was consistently among the three most highly activated muscles during each technique, which is in congruence with Kumar (1995b) who reported this muscle to be highly involved in pushing and pulling. The ramification is that this body region is likely to experience the greatest overall strain, validating previous concerns that the lower back may incur injury during pushing and pulling activities (Hoozemans **et al.**, 1998). Similarly, the triceps brachii, among the three most highly activated muscles during two techniques, was also likely to fatigue early, placing it at an elevated risk of overexertion.

Muscle Fatigue

During pushing and pulling the static nature of controlling and steering the manual vehicle (Garcin **et al.**, 1996; Hoozemans **et al.**, 1998) may lead to static loading of the muscle tissues in the upper body. Consequently, the increased load on the muscles may result in fatigue and overstrain of those muscles tissues. While parameters do exist indicating the magnitude of static contraction likely to result in the early onset of fatigue, there is, unfortunately, variability between values. For example; Sjøgaard **et al.** (1986) stated that contractions as low as 5%MVC when sustained for one hour would result in muscle fatigue, while Redfern (1992) reported a less conservative value of 10%MVC for prolonged periods. Employing the higher of the two limits as a frame of reference, Table XXX indicates the muscles violating this limit.

Erector spinae was the only muscle at risk of the early onset of fatigue across techniques and loads, implying that it will always be placed under great strain during pushing and pulling. While pushing and two-handed pulling at 250kg only

placed erector spinae at risk of early fatigue, at 500kg, more muscles exceeded the 10%MVC limit. The three most highly activated muscles during pushing (triceps brachii, anterior deltoid and erector spinae) and two-handed pulling (triceps brachii, posterior deltoid and erector spinae) always surpassed Redfern's limit, but in addition the medial deltoid was among this group during pushing. Comparatively, during one-handed pulling, the number of muscles violating the limit was higher at both loads. At 250kg, the three most highly activated muscles (brachioradialis, trapezius and erector spinae) were at risk, but at 500kg, in addition to these muscles, the triceps brachii, posterior deltoid and latissimus dorsi were likely to fatigue. Evidently, one-handed pulling is associated with the greatest likelihood of inducing early muscular fatigue in more muscles than either of the other techniques at both loads, implying that efforts should be made to avoid repetitively performing this task. At lower loads, it appears that either pushing or two-handed pulling are preferable, but as the load increases, both techniques place considerable strain on their respective three most highly activated muscles. During both techniques, the triceps brachii and erector spinae are strained, rendering recommendations less conclusive.

Comparison of Physical and Perceived Strain

Based on the argument that the demands of a task are related to perceived strain (Gamberale, 1985), perceptual responses of discomfort were compared to muscle activity. This entailed selecting the three most frequently rated areas for discomfort and the three most highly activated muscles during each technique at both loads to identify if discomfort manifested in the body areas eliciting the highest muscle activity. The results, depicted in Table XXXI, suggest that there is little uniformity between the two, suggesting a contradiction between perceived and actual physical strain. The adoption of a holistic integrated approach is thus pivotal to risk assessment, and will allow incongruities in recommendations to be addressed. Within this study, the disparities can possibly be attributed to the fact that the lower extremities, which were often perceived to feel discomfort, were not under electromyographic evaluation. Furthermore, although body regions may have been perceived to contribute to the exertions, the infrequent, short duration of the tasks performed, may not have necessarily induced discomfort.

Table XXXI. Comparison of perceived areas of discomfort with muscle activity

	Body discomfort 250kg	Muscle activity 250kg	Body discomfort 500kg	Muscle activity 500kg
Push	Calves, posterior forearms, middle back	Erector spinae	Calves	Anterior deltoid
		Triceps brachii	Forearms	Erector spinae
		Anterior deltoid	Biceps brachii	Triceps brachii
2-h pull	Calves	Erector spinae	Calves	Erector spinae
	Lower back	Triceps brachii	Lower back	Triceps brachii
		Posterior deltoid	Upper back, posterior deltoid, biceps brachii, hands	Posterior deltoid
1-h pull	Forearm	Erector spinae	Forearm	Brachioradialis
	Biceps brachii	Brachioradialis	Triceps brachii	Erector spinae
		Trapezius	Anterior deltoid, hand	Trapezius

 Highest muscle activity and most frequently rated areas of body discomfort
 Second highest muscle activity and second most frequently rated areas of body discomfort
 Third highest muscle activity and third most frequently rated areas of body discomfort

During pushing at both loads, there was no alignment of perceived and physical strain with reference to the three most frequently perceived areas of discomfort and the three most highly activated muscles. It is however important to note, that although not among the three highest regions to feel discomfort, the lower back still received multiple ratings, and was also found to be highly activated during pushing at 500kg. In accordance with the muscle activity ratings indicating high levels of activation in erector spinae at both loads, the lower back was also perceived to experience discomfort during two-handed pulling. Perhaps the most surprising discrepancies were that the shoulder muscles and triceps brachii tended to be highly activated during pushing and two-handed pulling at both loads, yet were not rated accordingly. Only the posterior deltoid was rated as feeling discomfort during two-handed pulling at 500kg. It was expected that due to these small muscles being placed under great strain, they would experience discomfort. During one-handed pulling, there was congruence between the most highly

activated muscle and the area perceived to feel the greatest discomfort, namely brachioradialis. Once again, although the lower back was not among the three most frequently rated muscles experiencing discomfort, it still received multiple ratings during one-handed pulling at 500kg and was also found to be highly activated. Whilst the lower extremities were not under investigation in this research, a crucial observation was the calves were rated most often during pushing and two-handed pulling, often at both loads. This suggests that the lower extremities may contribute grossly to pushing/pull exertions and are possibly areas of concern regarding overexertion injuries.

INTEGRATED DISCUSSION

To make a cohesive recommendation to industry as to which push/pull technique is preferable, an integration of measured responses is necessary. Not only are the demands of each task better appreciated, but this multifaceted approach largely circumvents the problems associated with making contradictory recommendations, which may adversely affect the musculoskeletal system. The integrated findings, based on the presence of statistically significant differences between conditions ($p < 0.05$) are illustrated in the lower half of Table XXXII, while the upper half represents the percentage of measured responses that are statistically different when comparing the conditions.

According to Table XXXII, the combination of technique and load had a considerable impact on all biomechanical variables, with all responses being at least 30% different between conditions. At 83% and 78%, the highest proportion of statistical differences occurred between one- and two-handed pulling at 250kg and 500kg respectively and between one- and two-handed pulling at 500kg and 250kg respectively, implying that these conditions are inherently dissimilar. Pertaining to the hypotheses under investigation, when comparing different techniques at the same loads, the lowest percentage of differences was evidenced between pushing and two-handed pulling at 250kg, where only 30% of measured responses were statistically different. These conditions thus influence the biomechanical variables in similar ways. When these two conditions were compared with one-handed

pulling at the same load, more differences existed (57% between pushing and one-handed pulling and 65% between two-and one-handed pulling).

Table XXXII. Statistically significant differences ($p<0.05$) of measures between conditions

	<i>Push 250kg</i>	<i>Push 500kg</i>	<i>2-h pull 250kg</i>	<i>2-h pull 500kg</i>	<i>1-h pull 250kg</i>	<i>1-h pull 500kg</i>
Push 250kg		52%	30%	61%	57%	74%
Push 500kg	Ini, sus, end SROM SV SA Brac, Ant, Med, Pos, Trap, Lat		57%	52%	52%	57%
2-h pull 250kg	SROM TV SA, TA Ant, Med, Trap	Ini, sus, end LROM, TROM LV, TV TA Brac, Ant, Med, Trap Lat		39%	65%	78%
2-h pull 500kg	Ini, sus, end SP SROM SV, TV SA, TA Tric, Ant, Pos, Lat, ES	Sus SP SROM, TROM LV, TV LA, TA Brac, Ant, Med, Trap	Ini, sus, end SP SROM SV Tric, Pos, Lat		83%	57%
1-h pull 250kg	LP, TP SROM, LROM, TROM TV TA Brac, Tric, Ant, Pos, Trap, Lat	Ini, sus, end LP, TP LROM, TROM TV SA Tric, Ant, Med	LP TP LROM, TROM LV, TV LA, TA Brac, Tric, Ant, Med, Pos, Trap, Lat	Ini, sus, end SP, LP, TP SROM, LROM, TROM SV, LV, TV SA, LA, TA Brac, Tric, Trap, ES		52%
1-h pull 500kg	Ini sus, end TP SROM, LROM, TROM SV, LV, TV SA, LA, TA Brac, Pos, Trap, Lat	Ini TP SROM, LROM, TROM TV TA Brac, Ant, Med, Pos, Trap, Lat	Ini, sus, end TP SROM, LROM, TROM SV, LV, TV LA, TA Brac, Ant, Med, Pos, Trap, Lat	SP, TP LROM, TROM LV, TV LA, TA Brac, Ant, Med, Trap, Lat	Ini, sus, end LP SROM, LROM SV SA Tric, Ant, Pos, Lat	

Ini =initial hand force
Sus =sustained hand force
End=ending hand force

Brac=brachioradialis
Tric =triceps
Pos =posterior deltoid

Ant =anterior deltoid
Med=medial deltoid
ES =erector spinae

Trap=trapezius
Lat =latissimus dorsi

SP=sagittal position
LP=lateral position
TP=transverse position

SROM=sagittal range
LROM=lateral range
TROM=transverse range

SV=sagittal velocity
LV=lateral velocity
TV=transverse velocity

SA=sagittal acceleration
LA=lateral acceleration
TA=transverse acceleration

At 500kg, all responses were statistically different by over 50%. Between pushing and two-handed pulling, 52% of the responses were significantly different but when these two techniques were compared with one-handed pulling at the same load, the differences increased by 5% in both cases, suggesting that the influence of technique on most variables was considerably different at high loads. Focusing on the impact of load across techniques, the fewest statistical differences occurred during pulling (39%), while differences in responses for pushing and one-handed pulling were higher at 52% for both. Comparatively, load had a less profound impact on two-handed pulling than on the other techniques.

CHAPTER VI

SUMMARY, CONCLUSION AND RECOMMENDATIONS

INTRODUCTION

Many industrial sectors are reliant on the use of manual vehicles to transport loads, requiring workers to perform repetitive pushing and pulling tasks. Despite arguments that these activities are less physically taxing than previous methods of load manipulation such as lifting, workers who perform pushing and pulling still reportedly experience pain and discomfort related to the lower back (Hoozemans *et al.*, 1998; Schibye *et al.*, 2001), shoulders and upper extremities (Hoozemans *et al.*, 1998; Hoozemans *et al.*, 2002), implying that the workload is still substantial. Although a necessary part of industrial work, efforts can be made to minimise the strain that labourers must endure while performing dynamic pushing and pulling by taking steps towards improving the work situation. Although environmental and operator factors cannot usually be altered, design and task factors, such as the way workers perform their jobs or changing the load mass to be displaced are practicable solutions.

A laboratory investigation was thus undertaken to determine the demands associated with using a standard industrial pallet jack, often evidenced in industry, to move loads of two different masses (250kg and 500kg) employing the three most widely adopted techniques of dynamic pushing and pulling. These were two-handed forward pushing, two-handed backward pulling and one-handed forward pulling. Essentially the aim was to identify differences between push/pull techniques through the biomechanical measures of hand forces, lumbar segment motion, upper body muscle activity and perceptual measures of body discomfort.

SUMMARY OF PROCEDURES

A sample of 36 healthy male university students (age= 21.69 ± 2.45 years, stature= 1796 ± 44 mm, mass= 78.41 ± 10.14 kg) volunteered to partake in this research. Participants attended one session of habituation and familiarisation in the Department of Human Kinetics and Ergonomics, where the objectives of the study were outlined, methodological procedures were explained and subjects were

familiarised with the use of the necessary equipment. They were provided with letters of information, instructions to follow prior to testing and instructions for use of the body discomfort scale to promote a better understanding of the study and, as far as possible, to address any concerns arising. At this stage participants were versed on how to initiate and terminate movement of the manual vehicle, allowing for consistency between subjects and conditions. Once familiar with the objectives and procedures, participants were permitted to query any uncertainties, after which written consent describing their willingness to partake was obtained. Demographic and anthropometric data including age, stature, mass, radiale and acromiale heights as well as hand dominance were recorded, ensuring that all subjects fulfilled the specified criteria relating to these factors. Stature was delimited to between 1700mm and 1900mm and only right-hand dominant individuals were included in the sample group. Ensuring that handle height was similar for all individuals facilitated measurement of radiale and acromiale heights, thereby minimising the effects of posture on measured responses. Once fully versed, participants were required to perform the requisite experimental conditions employing the pallet jack to be used in experimentation, until both the researcher and subject were fully satisfied that the tasks could be performed appropriately. Following this, participants selected suitable times for experimentation, with the only stipulation being that they should avoid any heavy physical activity 24 hours prior to testing, thereby preventing inaccurate results, particularly pertaining to myoelectric activity and body discomfort.

Each volunteer attended a further session of experimentation, lasting approximately 90 minutes. In this way, it was not necessary to replace and reposition the electrodes, which may have adversely affected intra-subject reliability (Lippold, 1952). This also permitted muscle activity to be more accurately expressed relative to maximum voluntary contractions (MVCs), which were performed in the same session prior to testing. Individuals performed six experimental conditions; two-handed forward pushing, two-handed backward pulling and one-handed forward pulling, each with two load masses (250kg and 500kg) using a standard industrial pallet jack, over a distance of 10m, along a wooden walkway. This surface provided an adequate coefficient of friction (0.4 to

0.6 as suggested by Sotter, 1995) to prevent slipping, whilst also maintaining a low rolling friction, to prevent the workload from imposing excessive physical strain on the musculoskeletal system. The recorded measures included hand force production, spinal kinematic variables, upper body muscle activity and body discomfort, which together aided in identifying the most optimal and detrimental dynamic pushing/pulling techniques. Preceding experimentation, the order in which conditions was executed was randomised, preventing any order effects.

Before subjects arrived, equipment was prepared and the Industrial Lumbar Motion Monitor was zero-calibrated in its storage case. On arrival, participants were reminded of the correct protocols to be followed, how to initiate and end movement of the pallet jack and how to use the body discomfort scale, after which they were prepared for testing. The hair on the muscle testing sites was shaved and the skin cleaned with an alcohol swab to augment conductivity between the skin and electrodes, following which two disposable pre-gelled silver chloride electrodes were placed on the appropriate muscle bellies on the right side of the body. Pilot investigations determined that muscles were equally active on the right and left sides of the body during the bilateral techniques and most active on the right side during the unilateral exertion as this was the side 'driving' the effort. Since muscle activation levels on the left were equally active or not active depending on the technique, this necessitated assessment of only the right side of the body. The electrodes were placed in a bipolar configuration on the muscle belly 20mm apart, and a neutral third was placed on passive tissue for grounding. Eight muscles on the upper body were assessed, each representing a major muscle involved in pushing and pulling efforts. Since surface electromyography only allows muscles directly beneath the skin to be assessed (Göbel, 2005), the muscles were also selected based on the proximity to the skin's surface. The muscles of interest were brachioradialis, triceps brachii, the three heads of the deltoids, the upper fibres of trapezius, latissimus dorsi and erector spinae. Following preparation, maximum voluntary contractions were performed whereby the muscles under investigation were individually isolated and contracted to their maximal capacity under external resistance. Subjects were then allotted a rest period, during which the iLMM was fitted and secured to the thorax. This

instrument was individually calibrated, with the participant standing in the upright bipedal stance and head directed in the Frankfurt-horizontal plane to allow all subsequent measurements to be recorded relative to the individual's pelvis and own lumbar curve.

During experimentation, participants were required to exert force against a load cell, the Chatillon® DFS Digital Force Gauge (AMETEK Inc., 2005), attached to the handle of the pallet jack. This permitted measurement of hand forces for each condition. Subjects performed three successful trials for each condition, with success being dictated by the correct walking speed and consistency of force exertion between trials per condition. Hand forces and spinal kinematic variables were measured for the duration of each successful trial, while myoelectric activity was measured continuously for the duration of experimentation. However the beginning and end of each trial were marked and the corresponding times were recorded for muscle activity. Finally, on completion of each condition, the perceived body discomfort and corresponding intensity ratings were recorded. This concluded experimentation.

All variables were analysed using descriptive statistics, following which two-way ANOVAS were performed to identify statistically significant differences between conditions. When comparing the hand forces elicited in each motion phase (initial, sustained and ending), a one-way ANOVA was performed. Muscle activity data were specifically transformed using the natural log function for normality, following which two-way ANOVAs were conducted. All analyses were performed at a 95% significance level ($p < 0.05$).

SUMMARY OF RESULTS

HAND FORCE EXERTION

Hand forces across techniques were statistically similar for each motion phase at 250kg, thus at lower loads, no one technique could be identified as optimal. However, as the load increased to 500kg, the contributing role of technique in determining the hand forces was more apparent, with pushing eliciting significantly higher initial forces than one-handed pulling and higher sustained forces than two-

handed pulling. While no significant differences existed during the ending phase at either load, the highest forces were related to one-handed pulling.

Comparison of hand forces between the motion phases (initial, sustained and ending) indicated that all were significantly different, with the initial forces being the highest and sustained forces, the lowest, irrespective of the combination of technique or load. Doubling the load moved from 250kg to 500kg significantly increased the magnitude of all hand forces, independent of the technique employed, but these were not consistent across motion phases. Mean increases of 64% and 58%, observed for the initial and ending forces respectively, were substantially lower than the increase of 145% seen in the sustained forces. Therefore, not only is load a critical determinant of hand force output when initiating and terminating movement of a manual vehicle, but increments in load mass make it a particularly pertinent consideration when maintaining motion too, as the sustained phase is likely to be related to fatigue and chronic injuries.

In line with existing recommendations, hand forces elicited at 250kg in all three motion phases, across all techniques, were within acceptable parameters. At 500kg, whilst all initial forces exceeded the proposed limits and were conclusively identified as unacceptable, determining the acceptability of the sustained forces was less definitive. Being below 112N, they were acceptable according to Eastman Kodak (1986) and Snook and Ciriello (1991), whereas the converse was true according to the HSE (1998), highlighting disparities in literature and legislation. Although ending forces were below the HSE (1998) guidelines of 245N, the lack of available literature necessitates tentative acceptance of this finding. Given that loads of 500kg, even in 'ideal' conditions may place considerable demands on the musculoskeletal system of the human operator, workers in industry are likely to experience the ill-effects of excessive task demands, since loads transported on any one trip may be as high as 1500kg (Mack *et al.*, 1995).

SPINAL KINEMATICS

Sagittal Plane

Impact of technique

Sagittal position was only affected by the technique employed at 500kg, with the highest spinal flexion occurring during two-handed pulling (17.44°), a finding which was statistically significant. The highest maximum sagittal ranges occurred during the pulling techniques (mean for both techniques 12.62° and 16.95° for 250kg and 500kg respectively), both of which were significantly higher than pushing responses at either load. While maximum velocities did not differ ($p>0.05$) between techniques, the greatest responses were associated with one- and two- handed pulling at both loads. Only at the lower load was maximum acceleration influenced by technique, with two-handed pulling responses being significantly higher than pushing responses.

Impact of load

Regarding sagittal position, only two-handed pulling was significantly affected by load mass, with an increase of 34% in trunk flexion when the load was doubled, suggesting that in the sagittal plane, two-handed pulling places individuals at a higher risk of developing lower back disorders. When assessing sagittal range, the heavier load caused significant increases, with the most profound increase occurring for two-handed pulling (43%), in accordance with the results associated with the sagittal position. Similar to the ranges, maximum sagittal velocities were all affected by the increase in load, with particularly large differences evidenced for pushing (increase of 36%). Contrary to results of the sagittal position and maximum ROM, the lowest increase occurred during two-handed pulling (21%) for maximum velocity. Maximum acceleration responses for pushing and one-handed pulling evidenced significant differences when the load was doubled, but two-handed pulling responses remained unaffected. Although two-handed pulling appears to be associated with a higher risk in the sagittal plane, cognisance must be taken of the fact that one-handed pulling elicited responses that were often similar to two-handed pulling. In this plane, pushing tended to impose the least risk.

Lateral Plane

Impact of technique

Unlike sagittal position, mean lateral position was only affected by technique at 250kg, with one-handed pulling evoking higher responses than the other two techniques, although acknowledgement must be made of the fact that all values were close to zero. One-handed pulling evidenced the highest maximum lateral ranges (14.81° and 19.42° for 250kg and 500kg respectively), while pushing and two-handed pulling responses were statistically similar. Maximum lateral velocities were affected by the technique employed at both loads; at 250kg responses for one-handed pulling were statistically greater than those of two-handed pulling. Although this difference existed at 500kg, pushing responses were also found to be statistically higher than those of two-handed pulling. Regarding maximum acceleration, at the lower load, one-handed pulling elicited higher responses than two-handed pulling, while at 500kg, one-handed pulling responses were found to be statistically higher than those elicited by both bilateral techniques.

Impact of load

Although load significantly affected lateral position, the absolute values were close to zero. With respect to maximum range, only one-handed pulling was accompanied by a significant increase in responses (by 4.61°) when the load was doubled. Since this technique was found to evoke higher responses than the other two techniques at both loads, this finding is important, and highlights that maximum lateral ROM is affected by the interplay between technique and load. Both maximum velocity and acceleration during pushing and one-handed pulling were accompanied by slight increases and two-handed pulling by a slight decrease when the load was doubled, although differences were not statistically verified. Generally one-handed pulling was associated with the highest risk in the lateral plane, but pushing was also of concern at 500kg with specific reference to maximum velocity and acceleration, which are important determinants of the risk of LBDs.

Transverse Plane

Impact of technique

Spinal kinematic responses in the transverse plane conclusively identified one-handed pulling as being associated with the highest risk, regardless of the load being transported. Regarding twisting position, at both loads one-handed pulling responses (18.69° and 16.69° for 250kg and 500kg respectively) were substantially higher than those for the other two techniques, which were close to zero, suggesting that technique has a considerable impact on this variable. The same differences were apparent with regard to maximum transverse ranges at both loads, but in addition, responses for pushing at 500kg were found to be statistically higher than those for two-handed pulling. For maximum velocity and acceleration, significant differences were evidenced between all techniques, with the highest relating to one-handed pulling and the lowest to two-handed pulling.

Impact of load

Importantly load did not have an effect on each technique with regard to mean twisting position, maximum twisting velocity and acceleration, reiterating the importance of technique on trunk motion characteristics in the transverse plane. Although no significant differences existed between loads across techniques, with reference to maximum transverse ranges, there was an overall effect. Responses were higher at 500kg, compared to 250kg (aggregated for all three techniques).

MUSCLE ACTIVITY

Eight muscles on various parts of the upper body were selected for investigation. These included two arm muscles (brachioradialis, triceps brachii), the shoulders (anterior, medial and posterior deltoids) and three back muscles (upper fibres of trapezius, latissimus dorsi and erector spinae). Based on their functional actions, each was differently involved in the pushing and pulling exertions.

Arm muscles

Technique affected the muscle activity of brachioradialis at both loads. At 250kg one-handed pulling evoked significantly higher responses than pushing, while at 500kg, it was found to elicit responses that were higher than either of the bilateral

techniques. Muscle activity of the triceps brachii was only affected by technique at the lower load, with one-handed pulling responses being statistically higher than those of pushing or two-handed pulling. The impact of load was evident for both muscles. In respect of brachioradialis, pushing responses were significantly affected, while in contrast to this, muscle activity of the triceps brachii during one- and two-handed pulling evidenced significant increases, the most pronounced of which was 115% relating to the asymmetrical technique.

Shoulder muscles

All techniques imposed statistically different muscle activation levels in the anterior deltoid at both loads, with the highest being associated with pushing and the lowest with two-handed pulling. In the medial deltoid, two-handed pulling was associated with the lowest muscle activity at both loads, and pushing the highest, although at 250kg, muscle activity for pushing and one-handed pulling were statistically similar. Regarding the posterior deltoid, compared to the other two techniques, one-handed pulling responses at 250kg were significantly higher, but at 500kg, although this technique evidenced the highest activity, responses were statistically similar to those for two-handed pulling.

An increase in load mass from 250kg to 500kg had a significant effect on the muscle activity of all three heads of the deltoid. In the anterior deltoid, both pushing and one-handed pulling responses increased significantly, with the most pronounced increase of 15.84%MVC being for pushing. In the medial deltoid only pushing responses increased by 5.9%MVC. Given that pushing was generally associated with the highest activity in the anterior and medial deltoids, the fact that increments in load amplified responses suggests that the risk of overstrain in these two gracile muscles concurrently increases with load during pushing tasks. Regarding the posterior deltoid, differences in muscle activity due to load were evidenced across all techniques, with the greatest impact observed for two-handed pulling, increasing by 74%.

Back muscles

The muscle activity of trapezius and latissimus dorsi identified one-handed pulling as imposing the greatest muscular strain, independent of load. For both muscles, one-handed pulling resulted in the highest muscles activity, while two-handed pulling and pushing responses were lowest for trapezius and latissimus dorsi respectively. Erector spinae muscle activity did not differ significantly between techniques at either load, although the overall effect suggested that responses for two-handed pulling (aggregated for both loads) were statistically higher than those for one-handed pulling.

Only during pushing did load affect muscle activation levels for trapezius, with the higher responses accompanying the 500kg load and resulting in the muscle activity approximately doubling. Load affected the muscle activity of latissimus dorsi in all three techniques, with the highest increase being for one-handed pulling (77%). Considering erector spinae, no statistical differences existed between loads for all techniques, however, it is important to note that this muscle elicited high activation levels for all six experimental conditions (in excess of 13.30%MVC at 250kg and 15.00%MVC at 500kg).

BODY DISCOMFORT

Subjective ratings of discomfort indicated that in general different body regions were selected during each technique. For the bilateral techniques, areas on both the right and left sides were identified while for one-handed pulling primarily areas on the right side experienced discomfort. During pushing, brachioradialis, the biceps brachii, lower back and calves were of concern. While the calves and lower back received the most ratings during two-handed pulling, the triceps, the anterior deltoid and brachioradialis experienced discomfort during one-handed pulling indicating that discomfort is felt in different parts of the body according to the technique used. Load was found to have an impact on perceptual discomfort, with a higher frequency of ratings and subsequently higher intensity of ratings being associated with 500kg. Perhaps one of the most pivotal findings was that the calves are grossly involved in pushing and pulling efforts and therefore the lower

extremities may be at risk of injury when these types of activities are performed, an area requiring further investigation.

RESPONSE TO HYPOTHESES

Hypothesis 1a

This hypothesis stated that no significant differences would exist between biomechanical responses for each technique at the same load. Referring to the hand forces, the null hypothesis is tentatively accepted, with only 11% of the hand forces being statistically different in all motion phases. With 57% of spinal kinematic variables being statistically different, this hypothesis is rejected. Finally, the hypothesis is rejected with respect to muscle activity as 65% of the activity levels between techniques were different at the same load.

Hypothesis 1b

This hypothesis stated that no significant differences would exist between perceptual responses (body discomfort) for each technique at the same load. Although differences were evidenced between the body areas and subsequent intensity ratings associated with perceived discomfort during each technique, it was not possible to verify this statistically, thereby resulting in tentative acceptance of the null hypothesis.

Hypothesis 2a

This hypothesis stated that no significant differences would exist between biomechanical responses for loads using the same technique. Regarding hand forces, the null hypothesis is rejected with statistical differences existing between all responses. Only 31% of spinal kinematic variables significantly differed at the two loads, leading to a tentative acceptance of the null hypothesis. With reference to muscle activity, the null hypothesis is rejected, as 54% of responses were statistically different.

Hypothesis 2b

This hypothesis stated that no significant differences would exist between perceptual responses (body discomfort) for loads using the same technique.

Despite differences being observed between the incidence and intensity of perceptual discomfort ratings at the two loads, these could not be statistically substantiated, thus the null hypothesis is tentatively accepted.

Hypothesis 3

This hypothesis stated that no significant differences would exist between the forces exerted during the initial, sustained and ending motion phases for the same condition. This hypothesis is rejected, with all motion phases yielding statistically different responses within each condition.

CONCLUSIONS

Based on the rejection or tentative acceptance of the null hypotheses, the results elucidate that altering the push/pull technique and/or load will affect the biomechanical and perceptual responses. Related to this, it is critical to acknowledge that technique affected spinal kinematic variables and muscle activity, but not hand forces, while load impacted hand forces and muscle activity, but not spinal kinematic measures, as evidenced in the occurrence of statistically significant differences.

HAND FORCE EXERTION

Although pushing was accompanied by the highest force production while initiating and maintaining movement of the pallet jack, it was only statistically different at 500kg. These findings suggest that technique may only play a role in determining the hand forces at high loads as evidenced by only 11% of hand forces eliciting significant differences.

Irrespective of the combination of technique and load, all hand forces were significantly different between motion phases; the initial phase evidenced the highest forces and the sustained, the lowest. However, when load mass was increased to 500kg, although there were subsequent increases in all forces across techniques, the most pronounced of these was evidenced in the sustained phase. Based on the premise that hand forces may be indices for the strain incurred, task factors that promote high forces should thus be minimised. Hoozemans **et al.**

(2004), however, argued that hand force exertion is not necessarily an accurate predictor of the mechanical stress experienced during pushing and pulling and cited direction of exertion (van der Beek **et al.**, 1999; de Looze **et al.**, 2000), posture and movement (Hoozemans **et al.**, 2004) as possible alternatives.

SPINAL KINEMATICS

Describing the preferable means of load transport using measures of spinal kinematics varied according to the cardinal plane being assessed. Within the sagittal plane, while two-handed pulling required individuals to maintain the highest degree of sagittal flexion, particularly at 500kg, the maximum sagittal ranges were also high for one-handed pulling. This suggests that both average position and range of motion factors should be considered in analysing spinal kinematic responses during pushing and pulling. In respect of maximum velocities and accelerations, two-handed pulling elicited the highest responses at the lower load, although some values were statistically similar to one-handed pulling responses. When the load mass was doubled, maximum ranges and velocities increased across techniques. While mean position during two-handed pulling was significantly increased with the increment in load mass, for acceleration the increase was seen in pushing and one-handed pulling responses. Within this plane, findings suggest that pushing tended to impose the least stress on L₅/S₁.

The highest responses for spinal kinematic variables in the lateral plane were most often evidenced during one-handed pulling, although pushing responses, specifically relating to maximum velocity and acceleration at the lower load were statistically similar. The increase in load had an impact on one-handed pulling with reference to lateral displacements, while across techniques load had no impact on velocity and acceleration. Results therefore suggest that one-handed pulling evoked the greatest mechanical strain in the lower back, and two-handed pulling, the least.

Transverse plane spinal kinematic measures concluded that one-handed pulling evoked the highest responses across all techniques, regardless of the load

moved, findings which were statistically verified. Moreover, load did not have a significant effect on measured responses across techniques.

All spinal kinematic variables were compared to a risk classification system, related to the proliferation of lower back disorders, developed by Marras **et al.** (1995). Although findings tend to imply that two-handed pulling is related to greater spinal loading in the sagittal plane, responses were considered low risk at both loads. While most spinal kinematic variables in the lateral plane for one-handed pulling were low risk, maximum acceleration at 500kg was of concern, placing individuals at a moderate risk. For the other two techniques, this variable was classified as low risk. Finally, maximum ROM, velocity and acceleration related to one-handed pulling in the transverse plane suggested that it is a high risk task. However it must be noted that maximum transverse velocities and accelerations for pushing were related to moderate to high risks. Overall, one-handed pulling is accompanied by the greatest risk of overtaxing the human body, a finding which was corroborated using the Lower Back Disorder Model (Marras **et al.**, 1993). According to this model, even at the lower load, the risk related to one-handed pulling equalled or exceeded that of other techniques at the high load.

MUSCLE ACTIVITY

The highest muscle activation levels were most frequently evidenced during one-handed pulling and pushing. Importantly the small gracile muscle groups were often highly activated during these techniques, and are therefore at a higher risk of fatigue and long-term injury.

The highest muscle activity in brachioradialis, trapezius and latissimus dorsi occurred during one-handed pulling, implying that these muscles (on only one side of the body) are likely to experience muscle strains and related musculoskeletal disorders, given that they must bear most of the workload. Muscle activity in the anterior and medial deltoids were generally found to be highest during pushing, although at 250kg, muscle activation levels were equally high in the medial deltoid during one-handed pulling. Posterior deltoid activity was highest for one-handed pulling at the lower load, but equally high for two-handed pulling at 500kg. Pushing

and two-handed pulling elicited the highest strain in the triceps brachii, but differences were only statistically significant at 250kg. Despite no significant differences between techniques regarding erector spinae muscle activity at each load, this muscle was among the three most highly activated muscles in all three techniques. As this is the case, although erector spinae will always display high activation levels, where pushing and pulling are required, workers should be encouraged to alternate between different techniques to prevent straining the same muscles continuously, thereby preventing cumulative stress. Where possible, job rotation would provide a suitable alternative. Despite two-handed pulling generally corresponding to the lowest levels of muscle activation, this finding should be accepted with caution as muscle activity in the lower extremities requires assessment.

Based on the effort exhibited by each muscle in relation to their MVCs, the three most highly activated muscles were identified at each technique. During pushing these were the anterior deltoid, triceps brachii and erector spinae. Of particular concern was that at 500kg the small anterior deltoid exhibited 22.96%MVC at the high load, the highest muscular effort during pushing. During two-handed pulling, the triceps brachii, posterior deltoid and erector spinae were most active, with the greatest increase in activity of the three muscles, due to load, being in the posterior deltoid (74%). Brachioradialis, trapezius and erector spinae were of concern during one-handed pulling, with brachioradialis activity being highest at 500kg. Evidently, load tends to have the most profound impact on the smaller, gracile muscles, implying that any additional increments in load are likely to result in these muscles fatiguing early.

BODY DISCOMFORT

While differences relating to the impact of technique and load on perceptual discomfort could not be confirmed statistically, both these independent variables affected responses. In general each technique was associated with different body regions being rated and furthermore the frequency of ratings, together with the intensity of ratings increased at 500kg. This research has established that the

lower extremities, particularly the calves may fulfil a critical role in all push/pull exertions, which may be an area for associated research to address in future.

RECOMMENDATIONS

Both industry and future research into pushing and pulling tasks may be assisted by the following recommendations, acknowledging that the quantified effects of potential risk due to push/pull technique and load are specific to the context of the present study and should be applied tentatively.

While the laboratory environment permits controlling confounding variables, by its very nature it does not allow findings to be wholly transferred to the industrial setting. Progress in this area may be made by conducting a combination of field and laboratory investigations. If this is not feasible, employing industrial workers in laboratory research may be a more appropriate alternative. Given that their anthropometric and demographic characteristics as well as physical capacities may vary considerably from sample groups, implying that results may not be accurate, this is warranted. Furthermore, the number of females entering the manual job market has increased, necessitating evaluations of female responses to push/pull tasks.

Although various biomechanical and perceptual measures provided a reasonable indication of the workload imposed by different push/pull techniques, the physiological costs of these tasks were not within the scope of this study. Given the variability of frequency and duration when performing repetitive pushing and pulling, as well as the fact that typical work shifts are eight hours long, the provision of physiological recommendations would prove to be invaluable. Coupled with biomechanical and perceptual measures, this would provide a more holistic integrated assessment of the task demands, minimising contradictory recommendations.

Despite a known linear relationship between load mass and hand forces, the present study has shown that recommendations need not only be context-specific, but motion-phase specific, since the type and degree of risk is likely to change

between motion phases, implying that each must be addressed accordingly. Furthermore, load, known to impact the hand forces exerted in all motion phases, has the most profound effect on sustained forces, which is likely to contribute to fatigue and cumulative injuries, confirming the importance of considering each motion phase and emphasising the minimisation of load mass wherever possible. However, as indicated by Hoozemans **et al.** (2004) the magnitude of hand forces may not necessarily indicate the stresses imposed on the musculoskeletal system, and therefore they should not be considered in isolation, but rather be considered in combination with other factors, such as posture, movement or direction of motion. Future studies are encouraged to consider the degree of risk related to each motion phase separately, and must additionally take heed of the fact that measures other than hand forces may indicate the degree of risk more accurately.

Future studies should be directed to further assess the impact of spinal motion during pushing and pulling, as this is one of the first studies to do so. This will aid in enhancing the limited body of knowledge surrounding this topic and provide a more rigorous understanding of the inherent risk in these types of activities. Related to this, although the static estimates of spinal load were obtained in the form of shear and compression estimates, a dynamic analysis tool may provide better insight into the mechanical load imposed on the spinal structures. Similarly, further investigation into the load experienced at the shoulder girdle, being an area found to elicit high muscle activity and experience subjective discomfort, is critical. To achieve this, models that not only consider joint torques but also compressive and shear forces experienced would be pivotal.

Since pushing and pulling tasks involve the whole body, they should be assessed accordingly, whereby cognisance is taken of the upper and lower extremities. This is justified, given that participants in this study subjectively rated the calves as experiencing discomfort. Furthermore, analysis of gait patterns may be warranted, as slip, trip and fall accidents, common occurrences in vocational settings, are often related to pushing and pulling. Additionally, future studies into muscle activity during push/pull tasks must take heed that some muscles are more resistant to fatigue than others due to a predominance of either slow or fast twitch fibres.

Due to various combinations of muscles being active during different techniques, where repetitive pushing and pulling are requisites, workers should be encouraged to employ different techniques throughout the day, thereby preventing the same muscles from being taxed continuously. Along similar lines, where possible, job rotation should be introduced to minimise the effects of cumulative injuries.

In attempts to make applicable recommendations to a broader array of industrial sectors, a wider range of loads should be evaluated. In addition, push/pull technique should be investigated in combination with other task, design and environmental factors to definitively identify which technique is ideal. Future studies are also encouraged to consider these techniques in relation to steerability and controllability of the manual vehicle as well as field of view.

Finally, where possible, asymmetrical one-handed pulling should be avoided. This has been shown to be accompanied by significant twisting in the lumbar spine and high levels of muscle activation. Furthermore, one-side of the body is required to shoulder most of the load, intensifying the risk of overexertion injuries. Although two-handed pulling has tentatively been shown to be associated with the lowest responses in most variables compared to the other two techniques, the field of view in the intended direction is obstructed. Therefore two-handed forward pushing may be a more suitable alternative.

REFERENCES

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

Adams MA and Dolan P (1995). Recent advances in lumbar spinal mechanics and their clinical significance. **Clinical Biomechanics**, 10(1): 3-19.

Al-Eisawi KW, Kerk CJ, Congleton JJ, Amendola AA, Jenkins OC and Gaines WG (1999a). The effect of handle height and cart load on the initial hand forces in cart pushing and pulling. **Ergonomics**, 42(8): 1099-1113.

Al-Eisawi KW, Kerk CJ, Congleton JJ, Amendola AA, Jenkins OC and Gaines WG (1999b). Factors affecting minimum push and pull forces of manual carts. **Applied Ergonomics**, 30: 235-245.

Allread WG, Marras WS and Burr DL (2000). Measuring trunk motions in industry: variability due to task factors, individual differences, and the amount of data collected. **Ergonomics**, 43(6): 691-701.

Anders C, Bretschneider S, Bernsdorf A, Erler K and Schneider W (2004). Activation of shoulder muscles in healthy men and women under isometric conditions. **Journal of Electromyography and Kinesiology**, 14: 699-707.

Andres RO and Chaffin DB (1991). Validation of a biodynamic model of pushing and pulling. **Journal of Biomechanics**, 24(11): 1033-1045.

Ayoub MM and McDaniel JW (1974). Effects of operator stance on pushing and pulling tasks. **Institute of Industrial Engineering Transactions**, 6(3), 185-195.

Ayoub MM, Selan JL and Liles DH (1983). An ergonomics approach for the design of manual materials-handling tasks. **Human Factors**, 25(5): 507-515.

Ayoub MM (1992). Problems and solutions in manual materials handling: the state of the art. **Ergonomics**, 35(7/8): 713-728.

Ayoub MM and Dempsey PG (1999). The psychophysical approach to manual materials handling task design. **Ergonomics**, 42(1):17-31.

Baril-Gingras G and Lortie M (1995). The handling of objects other than boxes: univariate analysis of handling techniques in a large transport company. **Ergonomics**, 38(5): 905-925.

Bennett AI (2006). The effect of load on the biomechanical, physiological and psychophysical responses during dynamic pulling. **Unpublished Research**. Department of Human Kinetics and Ergonomics. Rhodes University.

Bennett AI, Desai SD, Todd AI and Freeland H (2008). The effects of load and gradient on hand force responses during dynamic pushing and pulling tasks. **Ergonomics SA**, 20(1): 3-15.

Bigos SJ, Spengler DM, Marin NA, Zeh J, Fisher L, Nachemson A and Wang MH (1986). Back injuries in industry: a retrospective study II. Injury factors. **Spine**, 11(3): 246-251.

Bjelle A, Hagberg M and Michaelson G (1981). Occupational and individual factors in acute shoulder-neck disorders among industrial workers. **British Journal of Industrial Medicine**, 38: 356-363.

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

Borg G (1978). Subjective aspects of physical and mental load. **Ergonomics**, 21(3): 215-220.

Bos J, Kuijer PPFM and Frings-Dresen MHW (2006). Definition and assessment of specific occupational demands concerning lifting, pushing, and pulling based on a systematic literature search. **Occupational and Environmental Medicine**, 59(12): 800-806.

Chaffin DB, Andres RO and Garg A (1983). Volitional postures during maximal push/pull exertions in the sagittal plane. **Human Factors**, 25(5): 541-550.

Chaffin DB (1987). Occupational Biomechanics- a basis for workplace design to prevent musculoskeletal injuries. **Ergonomics**, 30(2): 321-329.

Chaffin DB, Stump BS, Nussbaum MA and Baker G (1999). Low-back stress when learning to use a materials handling device. **Ergonomics**, 42(1): 94-110.

Chaffin DB (2003). Static Biomechanical Modeling in Manual Lifting. In W Karwowski and WS Marras (eds): **Occupational Ergonomics: Engineering and Administrative Controls**. Boca Raton: CRC Press, pp. 11-1-11-12.

Charteris J (1982). Human gait cyclograms: conventions, speed relationships and clinical applications. **International Journal of Rehabilitation Research**, 5(4): 507-518.

Cholewicki J and McGill SM (1996). Mechanical stability of the *in vivo* lumbar spine: implications for injury and chronic low back pain. **Clinical Biomechanics**, 11(1): 1-15.

Ciriello VM, McGorry RW and Martin SE (2001). Maximum acceptable horizontal and vertical forces of dynamic pushing on high and low coefficient of friction floors. **International Journal of Industrial Ergonomics**, 27: 1-8.

Ciriello VM (2004). Comparison of two techniques to establish maximum acceptable forces of dynamic pushing for female industrial workers. **International Journal of Industrial Ergonomics**, 34(2):93-99.

Ciriello VM (2005). Psychophysically determined horizontal and vertical forces of dynamic pushing on high and low coefficient of friction floors for female industrial workers. **Journal of Occupational and Environmental Hygiene**, 2: 136-142.

Ciriello VM, Dempsey PG, Maikala RV and O'Brien NV (2008). Secular changes in psychophysically determined maximum acceptable weights and forces over 20 years for male industrial workers. **Ergonomics**, 51(5): 593-601.

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

*Corlett EN (1981). Pain, Posture and Performance. In EN Corlett and J Richardson (eds). **Stress, Work Design and Productivity**. London: Wiley, pp. 27-42. (see Haslegrave, 1994).

Cripwell AM (2007). The impact of load and frequency on the biomechanical, physiological and perceptual responses to dynamic pushing. **Unpublished Research**. Department of Human Kinetics and Ergonomics. Rhodes University.

Daams BJ (1993). Static force exertions in postures with different degrees of freedom. **Ergonomics**, 36(4): 397-406.

Das B, Wimpee J and Das B (2002). Ergonomics evaluation and redesign of a hospital meal cart. **Applied Ergonomics**, 33: 309-318.

*David GD and Nicholson AS (1985). **Aids to lifting and handling. The safety practitioner**. Leicester: Institution of Occupational Safety and Health. (see Jung **et al.**, 2005).

*Davis PR and Stubbs DA (1978). Safe levels of manual forces for young males (3). **Applied Ergonomics**, 9(1): 33-38. (see Schaub **et al.**, 2007).

Davis KG and Marras WS (2000). The effects of motion on trunk biomechanics. **Clinical Biomechanics**, 15: 703-717.

de Looze MP, Stassen ARA, Markslag AMT, Borst MJ, Wooning MM and Toussaint HM (1995). Mechanical loading on the low back in three methods of refuse collecting. **Ergonomics**, 38(10):1993-2006.

de Looze MP, van Greuningen K, Rebel J, Kingma I and Kuijer PPFM (2000). Force direction and physical load in dynamic pushing and pulling. **Ergonomics**, 43(3): 377-390.

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

Dempsey PG (1999). Utilising criteria for assessing multiple-task manual materials handling jobs. **International Journal of Industrial Ergonomics**, 24:405-416.

Dempsey PG and Hashemi L (1999). Analysis of workers' compensation claims associated with manual materials handling. **Ergonomics**, 42(1): 183-195.

Dempsey PG and Mathiassen SE (2006). On the evolution of task-based analysis of manual materials handling, and its applicability in contemporary ergonomics. **Applied Ergonomics**, 37: 33-43.

Desai SD (2006). Biomechanical, physiological and psychophysical responses to level and graded trolley pushing. **Unpublished Research**. Department of Human Kinetics and Ergonomics. Rhodes University.

*Donders NCGM, Hoozemans MJM, van der Beek AJ, Frings-Dresen MHW and van der Gulden JWJ (1997). Duwen en trekken van rollend materieel [in Dutch]. **Tijdschrift voor Ergonomie**, 22: 102-108. (see van der Beek **et al.**, 1999).

*Drury CG, Barnes RE and Daniels EB (1975). Pedestrian operated vehicles in hospitals. **Proceedings: Annual Conference of the American Institute of Industrial Engineers, Washington 20-23 May 1975**. 184-191. (see Jung **et al.**, 2005).

Drury CG, Deeb JM, Hartman B, Woolley S, Drury CE and Gallagher S (1989). Symmetric and asymmetric manual materials handling. Part 1: physiology and psychophysics. **Ergonomics**, 32(5): 467-489.

*Eastman Kodak (1986). **Ergonomics Design for People at Work. Volume 2**. New York: Van Nostrand Reinhold. (see Jung **et al.**, 2005).

Farfan HF, Cossette JW, Robertson GH, Wells RV and Kraus H (1970). The effects of torsion on the lumbar intervertebral joints: the role of torsion in the production of disc degeneration. **Journal of Bone and Joint Surgery**, 52: 468-497.

Ferguson SA, Marras WS and Waters TR (1992). Quantification of back motion during asymmetric lifting. **Ergonomics**, 35(7/8): 845-859.

Ferguson SA and Marras WS (2004). Revised protocol for the kinematic assessment of impairment. **The Spine Journal**, 4: 163-169.

Ferguson SA, Marras WS and Burr DL (2004). The influence of individual low back health status on workplace trunk kinematics and risk of low back disorder. **Ergonomics**, 47(11): 1226-1237.

Ferreira JJ, Boocock MG and Gray MI (2004). Review of the risk associated with pushing and pulling heavy loads. **Health and Safety Executive**. Norwich: HSE Books.

Fothergill DM, Grieve DW and Pheasant ST (1991). Human strength capabilities during one-handed maximum voluntary exertions in the fore and aft planes. **Ergonomics**, 34(5); 563-573.

Fothergill DM, Grieve DW and Pheasant ST (1992). The influence of some handle designs and handle height on the strength of the horizontal pulling action. **Ergonomics**, 35(2): 203-212.

Frings-Dresen MHW, Kemper HCG, Stassen ARA, Crolla IFAM and Markslag AMT (1995). The daily work load of refuse collectors working with three different collecting methods: a field study. **Ergonomics**, 38(10): 2045-2055.

Frymoyer JW, Pope MH, Costanza MC, Rosen JC, Goggin JE and Wilder DG (1980). Epidemiologic studies of low-back pain. **Spine**, 5(5): 419-423.

*Gagnon M, Beaugrand S and Authier M (1992). The dynamics of pushing loads onto shelves of different heights. **International Journal of Industrial Ergonomics**, 9: 1-13. (see Kumar, 1995a).

Gallagher S, Marras WS, Davis KG and Kovacs K (2002). Effects of posture on dynamic back loading during a cable lifting task. **Ergonomics**. 45(5): 380-398.

Gallagher S and Moore JS (2003). Worker strength evaluation: job design and worker selection. In W Karwowski and WS Marras (eds). **Occupational Ergonomics: Principles of Work Design**. Boca Raton: CRC Press, pp. 21-1-21-16.

Gamberale F (1985). The perception of exertion. **Ergonomics**, 28(1): 299-308.

Garcin M, Cravic JY, Vandewalle H and Monod H (1996). Physiological strains while pushing or hauling. **European Journal of Applied Physiology**, 72: 478-482.

Garg A, Funke S and Janisch D (1988). One-handed dynamic pulling strength with special application to lawn mowers. **Ergonomics**, 31: 1139-1153.

Gill KP and Callaghan MJ (1996). Intratester and intertester reproducibility of the lumbar motion monitor as a measure of range, velocity and acceleration of the thoracolumbar spine. **Clinical Biomechanics**, 11(7): 418-421.

Glitsch U, Ottersbach HJ, Ellegast R, Schaub K, Franz G and Jäger M (2007). Physical workload of flight attendants when pushing and pulling trolleys aboard aircraft. **International Journal of Industrial Ergonomics**, 37(11/12): 845-854.

Göbel M (2005). Electromyography (EMG). In N Stanton, A Hedge, K Broohuis, E Salas and H Hendrick (eds). **Handbook of Human Factors and Ergonomics Methods**. Boca Raton: CRC Press, pp. 19-1-19-8.

Granata KP and Marras WS (1995). The influence of trunk muscle coactivity upon dynamic spinal loads. **Spine**, 20: 913-919.

Granata KP and Marras WS (1999). Relation between spinal load factors and the high-risk probability of occupational low-back disorder. **Ergonomics**, 42(9): 1187-1199.

Granata KP and Orishimo K (2001). Response of trunk muscle coactivation to changes in spinal stability. **Journal of Biomechanics**, 34: 1117-1123.

Granata KP and Bennett BC (2005). Low-back biomechanics and static stability during isometric pushing. **Human Factors**, 47(3): 536-549.

Granata KP, Lee PE and Franklin TC (2005). Co-contraction recruitment and spinal load during isometric trunk flexion and extension. **Clinical Biomechanics**, 20: 1029-1037.

Grant KA and Habes DJ (1997). An electromyographic study of strength and upper extremity muscle activity in a simulated meat cutting task. **Applied Ergonomics**, 28(2): 129-137.

Haslam RA, Boocock M, Lemon P and Thorpe S (2002). Maximum acceptable loads for pushing and pulling on floor surfaces with good and reduced resistance to slipping. **Safety Science**, 40(7-8): 625 – 637.

Haslegrave CM (1994). What do we mean by a 'working posture'? **Ergonomics**, 37(4): 781-799.

*Health and Safety Executive (HSE) (1998). **Manual Handling. Manual Handling Operations Regulations 1992: Guidance on Regulations. L23, ISBN 0 7176 2415 3**. Second Edition. Suffolk: HSE Books. (see Ferreira *et al.*, 2004).

Hindle RJ, Pearcy MJ, Cross AT and Miller DHT (1990). Three-dimensional kinematics of the human back. **Clinical Biomechanics**, 5: 218-228.

Hoozemans MJM, van der Beek AJ, Frings-Dresen MHW, van Dijk FJH and van der Woude LHV (1998). Pushing and pulling in relation to musculoskeletal disorders: a review of risk factors. **Ergonomics**, 41(6): 757-781.

Hoozemans MJM, van der Beek AJ, Frings-Dresen MHW, van der Woude LHV and Dijk FJH (2002). Pushing and pulling in association with low back and shoulder complaints. **Occupational and Environmental Medicine**, 59: 696-702.

Hoozemans MJM, Kuijer PPFM, Kingma I, van Dieën JH, de Vries WHK, van der Woude LHV, Veeger DJ, van der Beek AJ and Frings-Dresen MHW (2004). Mechanical loading of the low back and shoulders during pushing and pulling activities. **Ergonomics**, 47(1): 1-18.

Hoozemans MJM, Slaghuys W, Faber GS and van Dieën (2007). Cart pushing: the effects of magnitude and direction of the exerted push force, and of trunk inclination on low back loading. **International Journal of Industrial Ergonomics**, 37(11/12): 832-844.

Illyés Á and Kiss RW (2005). Shoulder muscle activity during pushing, pulling, elevation and overhead throw. **Journal of Electromyography and Kinesiology**, 15: 282-289.

Imrhan SH (2003). Push-pull Force Limits. In W Karwowski and WS Marras (eds). **Occupational Ergonomics: Principles of Work Design**. Boca Raton: CRC Press, pp. 23-1-23-12.

Jäger M and Luttmann A (1999). Critical survey on the biomechanical criterion in the NIOSH method for the design and evaluation of manual lifting tasks. **International Journal of Industrial Ergonomics**, 23: 331-337.

Jäger M, Sawatzki K, Glitsch U, Ellegast R, Ottersbach HJ, Schaub K, Franz G and Luttmann A (2007). Load on the lumbar spine of flight attendants during pushing and pulling trolleys aboard aircraft. **International Journal of Industrial Ergonomics**, 37(11/12): 863-876.

James J, Cripwell A and Furney S (2005). Pushing vs. pulling strength: effect of handle height and practical ergonomics applications. **Proceedings 4th International Cyberspace Conference on Ergonomics. Johannesburg, 15 September-15 October**.

Jansen JP, Hoozemans MJM, van der Beek AJ and Frings-Dresen MHW (2002). Evaluation of ergonomic adjustments of catering carts to reduce external pushing forces. **Applied Ergonomics**, 33: 117-127.

Järvinen J and Lu H (2003). A guide to computer software for ergonomics. In W Karwowski and WS Marras (eds). **Occupational Ergonomics: Principles of Work Design**. Boca Raton: CRC Press, pp. 29-1-29-9.

Jonsson B (1988). The static load component in muscle work. **European Journal of Applied Physiology**, 57: 305-310.

Jung ES and Freivalds A (1991). Multiple criteria decision-making for the resolution of conflicting ergonomic knowledge in manual materials handling. **Ergonomics**, 34(11): 1351-1356.

Jung M, Haight, JM and Freivalds A (2005). Pushing and pulling carts and two-wheeled hand trucks. **International Journal of Industrial Ergonomics**, 35(1): 79-89.

Kendall FP, McCreary EK and Provance PG (1993). **Muscles: Testing and Function with Posture and Pain**. Fourth Edition. Baltimore: Wilkins & Wilkins.

Kingma I, Kuijer PPFM, Hoozemans MJM, van Dieën JH, van der Beek AJ and Frings-Dresen MHW (2003). Effect of design of two-wheeled containers on mechanical loading. **International Journal of industrial Ergonomics**, 31: 73-86.

Kroemer KHE (1969). Push forces exerted in 65 common work positions. **Aerospace Medical Research Lab Technical Report, USAF AMRL-TR-68-143**. Ohio: Wright Patterson Air Force Base.

Kuijer PPFM, Hoozemans MJM and Frings-Dresen MHW (2007). A different approach for the ergonomic evaluation of pushing and pulling in practice. **International Journal of Industrial Ergonomics**, 37(11/12): 855-862.

Kuiper JI, Burdorf A, Verbeek JHAM, Frings-Dresen MHW, van der Beek AJ and Vikari-Juntura ERA (1999). Epidemiologic evidence on manual materials handling as a risk factor for back disorders: a systematic review. **International Journal of Industrial Ergonomics**, 24(4): 389-404.

Kumar S (1995a). Upper body push-pull strength of normal young adults in sagittal plane at three heights. **International Journal of Industrial Ergonomics**, 15: 427-436.

Kumar S (1995b). Electromyography of spinal and abdominal muscles during garden raking with two rakes and rake handles. **Ergonomics**, 38(9): 1793-1804.

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

Kumar S (1996). Electromyography in ergonomics. In S Kumar and A Mital (eds). **Electromyography in Ergonomics**. Padstow: Taylor & Francis, pp. 1-49.

Laursen B and Schibye B (2002). The effect of different surfaces on biomechanical loading of shoulder and lumbar spine during pushing and pulling of two-wheeled containers. **Applied Ergonomics**, 33: 167-174.

Lavender SA, Chen S, Li Y and Andersson GBJ (1998). Trunk muscle use during pulling tasks: effects of a lifting belt and footing conditions. **Human Factors**, 40(1): 159-172.

*Lawson J, Potiki J and Watson H (1993). Development of ergonomic guidelines for manually handled trolleys in the health industry. **Journal of Occupational Health and Safety- Australia and New Zealand**, 9(5): 459-465. (see Jung et al., 2005).

Leamon TB (1994). Research to reality: a critical review of the validity of various criteria for the prevention of occupationally induced low back pain disability. **Ergonomics**, 37(12): 1959-1974.

Lee KS, Chaffin DB, Waikar AM and Chung MK (1989). Lower back muscle forces in pushing and pulling. **Ergonomics**, 32(12): 1551-1563.

Lee KS, Chaffin DB, Herrin GD and Waikar AM (1991). Effect of handle height on lower-back loading in cart pushing and pulling. **Applied Ergonomics**, 22(2): 117-123.

*Lee KS, Chaffin DB and Parks C (1992). A study of slip potential during cart pushing and pulling. **Institute of Industrial Engineering Transactions**, 24(5): 139-146. (see Hoozemans **et al.**, 1998).

Lee PJ and Granata KP (2006). Interface stability influences torso muscle recruitment and spinal load during pushing tasks. **Ergonomics**, 49(3): 235-248.

Lett KK and McGill SM (2006). Pushing and pulling; personal mechanics influence spine loads. **Ergonomics**, 49(9): 895-908.

LeVeau B and Andersson G (1992). Output Forms: Data Analysis and Applications: Interpretation of the Electromyographic Signal. In GL Soderberg (ed). **Selected Topics in Surface Electromyography for Use in the Occupational Setting: Expert Perspectives. NIOSH Publication No. 91-100**. U.S. Department of Health and Human Services, pp. 70-95.

Li KW, Chang C and Chang W (2008). Slipping of the foot on the floor when pulling a pallet truck. **Applied Ergonomics**, 39(6): 812-819.

Lippold OCJ (1952). The relation between integrated action potentials in a human muscle and its isometric tension. **Journal of Physiology**, 117: 492-499.

Louhevaara V (2003). Job demands and physical fitness. In Karwowski W and Marras WS (eds). **Occupational Ergonomics: Principles of Work Design**. Boca Raton: CRC Press, pp. 14-1-14-13.

Mack K, Haslegrave CM and Gray MI (1995). Usability of manual handling aids for transporting materials. **Applied Ergonomics**, 26(5): 353-364.

Maetzi A and Li L (2002). The economic burden of low back pain: a review of studies published between 1996 and 2001. **Best Practice and Research Clinical Rheumatology**, 16(1): 23-30.

*Manning DP, Mitchell RG and Blanchfield LP (1984). Body movements and events contributing to accidental and non-accidental back injuries. **Spine**, 9: 734-739. (see Hoozemans **et al.**, 1998).

Marras WS (1992). Overview of Electromyography in Ergonomics. In GL Soderberg (ed). **Selected Topics in Surface Electromyography for Use in the Occupational Setting: Expert Perspectives. NIOSH Publication No. 91-100**. U.S. Department of Health and Human Services, pp. 2-4.

Marras WS, Fathallah FA, Miller RJ, Davis SW and Mirka GA (1992). Accuracy of a three-dimensional lumbar motion monitor for recording dynamic trunk motion characteristics. **International Journal of Industrial Ergonomics**, 9: 75-87.

Marras WS, Lavender SA, Leurgans SE, Rajulu SL, Allread WG, Fathallah FA and Ferguson SA (1993). The role of dynamic three-dimensional trunk motion in occupationally-related low back disorders. **Spine**, 18(5): 617-628.

Marras WS, Lavender SA, Leurgans SE, Fathallah FA, Ferguson SA, Allread WG and Rajulu SL (1995). Biomechanical risk factors for occupationally related low back disorders. **Ergonomics**, 38(2): 377-410.

Marras WS and Granata KP (1997). The development of an EMG-assisted model to assess spine loading during whole-body free-dynamic lifting. **Journal of Electromyography and Kinesiology**, 7(4): 259-268.

Marras WS, Fine LJ, Ferguson SA and Waters TR (1999). The effectiveness of commonly used lifting assessment methods to identify industrial jobs associated with elevated risk of low-back disorder. **Ergonomics**, 42(1): 229-245.

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

Marras WS, Allread WG, Burr DL and Fathallah FA (2000). Prospective validation of a low-back disorder risk model and assessment of ergonomics interventions associated with manual materials handling tasks. **Ergonomics**, 43(11): 1866-1886.

Marras WS (2003a). The case for cumulative trauma in low back disorders. **The Spine Journal**, 3: 177-179.

Marras WS (2003b). Occupational Biomechanics. In W Karwowski and WS Marras (eds). **Occupational Ergonomics: Principles of Work Design**. Boca Raton: CRC Press, pp. 10-1-10-38.

Marras WS (2003c). Dynamic Workplace Factors in Manual Lifting. . In W Karwowski and WS Marras (eds). **Occupational Ergonomics: Principles of Work Design**. Boca Raton: CRC Press, pp. 22-1-22-19.

Marras WS, Allread WG and Ried RG (2003). In W Karwowski and WS Marras (eds). **Occupational Ergonomics: Engineering and Administrative Controls**. Boca Raton: CRC Press, pp. 18-1-18-26.

Marras WS (2005). The future of research in understanding and controlling work-related low back disorders. **Ergonomics**, 48(5): 464-477.

Marras WS and Allread WG (2005). Lumbar Motion Monitor. In N Stanton, A Hedge, K Broohuis, E Salas and H Hendrick (eds). **Handbook of Human Factors and Ergonomics Methods**. Boca Raton: CRC Press, pp. 14-1-14-7.

Marras WS (2006). Biomechanical Basis for Ergonomics. In WS Marras and W Karwowski (eds). Second Edition. **The Occupational Ergonomics Handbook: Fundamentals and Assessment Tools for Occupational Ergonomics**. Boca Raton: Taylor& Francis, pp. 11-1-11-43.

*Martin JB and Chaffin DB (1972). Biomechanical computerized simulation of human strength in sagittal plane activities. **American Institute of Industrial Engineering Transactions**, 4: 19-28. (see Kumar, 1995a).

*Mathisson B, Ingelgard A, Johnasson MI and Nonas K (1994). Mechanical aids in manual materials handling- technical context and attitudes. **Proceedings of the 12th Triennial Congress of the International Ergonomics Association, Toronto, 15-19th August 1994**. 33-37. (see Mack et al., 1995).

*McGill SM and Norman RW (1985). Dynamically and statically determined low back moments during lifting. **Journal of Biomechanics**, 8: 877-885. (see Granata and Marras, 1999)

McGill SM (1997). The biomechanics of low back injury: implications on current practice in industry and the clinic. **Journal of Biomechanics**, 30(5): 465-475.

Mirka G and Shin G (2006). Low back injury risk assessment tools. In WS Marras and W Karwowski (eds). Second Edition. **The Occupational Ergonomics Handbook: Fundamentals and Assessment Tools for Occupational Ergonomics**. Boca Raton: Taylor& Francis, pp.35-1-35-11.

Mital A, Nicholson AS and Ayoub MM (1993). **A Guide to Manual Materials Handling**. London: Taylor & Francis.

Mital A, Kopardekar P and Motorwala A (1995). Isokinetic pull strengths in the vertical plane: effects of speed and arm angle. **Clinical Biomechanics**, 10: 110-112.

Mital A (1999). Analysis of multiple activity manual materials handling tasks using A Guide to Manual Materials Handling. **Ergonomics**, 42(1): 246-257.

Mital A and Ramakrishnan A (1999). A comparison of literature-based design recommendations and experimental capability data for a complex manual materials handling activity. **International Journal of Industrial Ergonomics**, 24(1): 73-80.

Monahan T (1988). Perceived exertion: an old exercise tool finds new applications. **The Physician and Sports Medicine**, 16(10): 174-179.

*National Institute for Occupational Safety and Health (1981). **Work Practices Guide for Manual Load Lifting. NIOSH Technical Report No. 81-122**. U.S. Department of Health and Human Services. (see Waters et al., 1993).

*Nilsson S and Dahlman S (1994). Factors influencing the adoption of ergonomically improved working tools- a study comparing two 'equivalent' types of lifting carts. **Proceedings: 12th Triennial Congress of the International Ergonomics Association, Toronto, 15-19 August 1994**. (see Jung et al., 2005).

Nussbaum MA and Chaffin DB (1999). Effects of pacing when using materials handling manipulators. **Human Factors**, 41 (2): 214-225.

Nussbaum MA, Chaffin DB, Stump BS, Baker G and Foulke J (2000). Motion times, hand forces, and trunk kinematics when using material handling manipulators in short-distance transfers of moderate mass objects. **Applied Ergonomics**, 31: 227-237.

Okunribido OO and Haslegrave CM (1999). Effect of handle design for cylinder trolleys. **Applied Ergonomics**, 30: 407-419.

Okunribido OO and Haslegrave CM (2008). Ready steady push-a study of the role of arm posture in manual exertions. **Ergonomics**, 51(2): 192-216.

*Pheasant ST, Grieve DW, Rubin T and Thompson SJ (1982). Vector representations of human strength in whole body exertion. **Applied Ergonomics**, 13(2): 139-144. (see Fothergill et al., 1992).

Pheasant S and Haslegrave CM (2006). **Bodyspace: Anthropometry, Ergonomics and the Design of Work**. Third Edition. Boca Raton: Taylor and Francis.

Piedrahita H (2006). Costs of work-related musculoskeletal disorders (MSDs) in developing countries: Colombia Case. **International Journal of Occupational Safety and Ergonomics**, 12(4); 379-386.

Pope MH (1989). Risk indicators in low back pain. **Annals of Medicine**, 21: 387-392.

Redfern MS (1992). Functional Muscle: Effects on Electromyographic Output. In GL Soderberg (ed). **Selected Topics in Surface Electromyography for Use in the Occupational Setting: Expert Perspectives**. NIOSH Publication No. 91-100. U.S. Department of Health and Human Services, pp. 104-120.

Resnick ML and Chaffin DB (1995). An ergonomic evaluation of handle height and load in maximal and submaximal cart pushing. **Applied Ergonomics**, 26(3): 173-178.

Resnick ML and Chaffin DB (1997). An ergonomic evaluation of three classes of material handling device (MHD). **International Journal of Industrial Ergonomics**, 19: 217-229.

Rodrick D and Karwowski W (2006). Manual Materials Handling. In G Salvendy (ed). Third Edition. **Handbook of Human Factors and Ergonomics**. Hoboken: John Wiley & Sons, pp. 818-854.

Schaub K, Berg K, Winter G, Ellegast R, Glitsch U, Ottersbach HJ, Jäger M and Franz G (2007). Muscular capabilities and workload of flight attendants for pushing and pulling trolleys aboard aircraft. **International Journal of Industrial Ergonomics**, 37(11/12): 883-892.

Schibye B, Søgaaard K, Martinsen D and Klausen K (2001). Mechanical load on the low-back and shoulders during pushing and pulling of two-wheeled waste containers compared with lifting and carrying of bags and bins. **Clinical Biomechanics**, 16(7): 549-559.

Schultz A and Andersson G (1981). Analysis of loads on the lumbar spine. **Spine**, 6(1): 76-82.

*Shirazi-Adl A (1989). Strain in fibers of a lumbar disc: analysis of the role of lifting in producing disc prolapse. **Spine**, 14: 96-103. (see Marras **et al.**, 1995).

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

Silanpaa J, Lappalainen J, Kaukiainen A, Viljanen M and Laippala P (1999). Decreasing the physical workload of construction work with the use of four auxiliary hand devices. **International Journal of Industrial Ergonomics**, 24(2): 211-222.

*Sjøgaaard G, Kiens B, Jørgensen K and Saltin B (1986). Intramuscular pressure, EMG and blood flow during low-level prolonged static contraction in man. **Acta Physiol Scand**, 128: 475-484. (see Jonsson, 1988).

*Smith A (1776). An inquiry into the nature and causes of the wealth of nations, **Random House Modern Library College Edition**. (see Dempsey and Mathiassen, 2006).

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

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

Soderberg GL (1992). Recording techniques. In GL Soderberg (ed). **Selected Topics in Surface Electromyography for Use in the Occupational Setting: Expert Perspectives**. NIOSH Publication No. 91-100. U.S. Department of Health and Human Services, pp. 23-41.

Søgaaard K, Laursen B, Jensen BR and Sjøgaaard G (2001). Dynamic loads on the upper extremities during two different floor cleaning methods. **Clinical Biomechanics**, 16: 866-879.

Song YW and Chung MK (2004). Quantitative assessment of trunk muscle coactivation in sub-maximal isometric exertion tasks. **International Journal of Industrial Ergonomics**, 34: 13-20.

*Sotter G (1995). Friction underfoot. **Occupational Health and Safety March**, 28-34. (see Ciriello *et al.*, 2001).

Spengler DM, Bigos SJ, Martin NA, Zeh J, Fisher L and Nachemson A (1986). Back injuries in industry: a retrospective study. 1. overview and cost analysis. **Spine**, 11(3): 241-251.

Statsoft Inc. (2008). STATISTICA (data analysis software system), version 8.0. www.statsoft.com

Straker LM, Stevenson MG and Twomey LT (1996). A comparison of risk assessment of single and combination manual handling tasks: 1. Maximum acceptable weight measures. **Ergonomics**, 39(1): 128-140.

St-Vincent M, Denis D, Imbeau D and Laberge M (2005). Work factors affecting manual materials handling in a warehouse superstore. **International Journal of Industrial Ergonomics**, 35: 33-46.

Todd AI (2005). Current trends in research focused on pushing and pulling. **Proceedings: 4th International Cyberspace Conference on Ergonomics. Johannesburg, 15 September-15 October 2005.**

Tola S, Riihimäki H, Videman T, Viikari-Juntura E and Hänninen K (1988). Neck and shoulder symptoms among men in machine operating, dynamic physical work and sedentary work. **Scandinavian Journal of Work Environment and Health**, 14: 299-305.

van der Beek AJ, Hoozemans MJM, Frings-Dresen MHW and Burdorf A (1999). Assessment of exposure to pushing and pulling in epidemiological field studies: an overview of methods, exposure measure, and measurement strategies. **International Journal of Industrial Ergonomics**, 24: 417-429.

van der Beek AJ, Kluvers BDR, Frings-Dresen MHW and Hoozemans MJM (2000). Gender differences in exerted forces and physiological load during pushing and pulling in wheeled cages by postal workers. **Ergonomics**, 43(2): 269-281.

van Dieën JH and Oude Vrielink HHE (1998). Evaluation of work-rest schedules with respect to the effects of postural workload in standing work. **Ergonomics**, 41(12): 1832-1844.

van Nieuwenhuyse A, Fatkhutdinova L, Verbeke G, Pirenne D, Johannik K, Somville PR, Mairiaux PH, Moens GF and Masschelein R (2004). Risk factors for the first-ever low back pain among workers in their first employment. **Occupational Medicine**, 54: 513-519.

Warwick D, Novak G, Schultz A and Berkson M (1980). Maximum voluntary strengths of male adults in some lifting, pushing and pulling activities. **Ergonomics**, 23(1): 49-54.

Waters TR, Putz-Anderson V, Garg A and Fine LJ (1993). Revised NIOSH equation for the design and evaluation of manual lifting tasks. **Ergonomics**, 36(7): 749-776.

*Webster BS and Snook SH (1994). The cost of 1989 workers' compensation low back pain claims. **Spine**, 19(10): 1111-1115. (see Marras, 2000).

*Winkel J (1983). On the manual handling of wide-body carts used by cabin attendants in civil aircraft. **Applied Ergonomics**, 14(3): 162-168. (see Mack **et al.**, 1995).

Yingling VR, Callaghan JP and McGill SM (1997). The porcine cervical spine as a model of the human lumbar spine: an anatomical, geometric, and functional comparison. **Journal of Spinal Disorders**, 12(5): 415-423.

BIBLIOGRAPHY

Note: The following sources were consulted by the author during the conceptual growth of this dissertation. While not specifically cited, these works did play an important role in establishing the basis upon which thesis research was developed.

Ayoub MM and Mital A (1989). **Manual Materials Handling**. Taylor and Francis London.

Borg G (1982). Psychophysical basis of perceived exertion. **Medicine and Science in Sports and Exercise**, 14(5): 377-381.

Buckle P (2005). Ergonomics and musculoskeletal disorders: overview. **Occupational Medicine**, 55: 164-167.

Ciriello VM, Snook SH, Hashemi L and Cotnam J (1999). Distributions of manual materials handling task parameters. **International Journal of Industrial Ergonomics**, 24: 379-388.

Ciriello VM, McGorry RW, Martin SE and Bezverkhny IB (1999). Maximum acceptable forces of dynamic pushing; comparison of two techniques. **Ergonomics**, 42(1): 32-39.

Datta SR, Chatterjee BB and Roy BN (1978). The energy cost of rickshaw pulling. **Ergonomics**, 21(11): 879-886.

Datta SR, Chatterjee BB and Roy BN (1983). The energy cost of pulling hand carts ('thela'). **Ergonomics**, 26(5): 461-464.

Genaidy AM, Al-Shedi AA and Karwowski W (1994). Postural stress analysis in industry. **Applied Ergonomics**, 25(2): 77-87.

Genaidy AM, Karwowski W, Christensen DM, Vodiatzis C, Deraiseh N and Prins A (1998). What is heavy? **Ergonomics**, 41(4): 420-432.

Granata KP, Marras WS and Davis KG (1999). Variation in spinal load and trunk dynamics during repeated lifting exertions. **Clinical Biomechanics**, 14: 367-375.

Hägg GM, Luttmann A and Jäger M (2000). Methodologies for evaluating electromyographic field data in ergonomics. **Journal of Electromyography and Kinesiology**, 10: 310-312.

Kee D and Chung MK (1996). Comparison of prediction models for the compression forces on the lumbosacral disc. **Ergonomics**, 39(12): 1419-1429.

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

Marras WS and Mirka GA (1989). Trunk strength during asymmetric trunk motion. **Human Factors**, 31(6): 667-677.

Marras WS and Mirka GA (1990). Trunk responses to asymmetric acceleration. **Journal of Orthopaedic Research**, 8: 824-832.

McArdle WD, Katch FI and Katch VL (2001). **Exercise Physiology. Energy, Nutrition and Human Performance**. Fifth edition. Baltimore: Lippincott Williams and Wilkins.

McKinnon SN (2002). Effects of standardised foot positions during the execution of a submaximal pulling task. **Ergonomics**, 45(4):253-266.

Nadeau S and Gagnon M (1996). Work and energy transfers in maximal pushing of loads. **International Journal of Industrial Ergonomics**, 17: 221-234.

Nicholson LM and Legg SJ (1986). A psychophysical study of the effects of load and frequency upon selection of workload in repetitive lifting. **Ergonomics**, 29(7): 903-911.

Smolander J, Louhevaara V, Ahonen E, Polari J and Klen T (1995). Energy expenditure and clearing snow: a comparison of shovel and snow pusher. **Ergonomics**, 38(4): 749-753.

Vasseljen O and Westgaard RH (1997). Arm and trunk posture during work in relation to shoulder and neck pain and trapezius activity. **Clinical Biomechanics**, 12(1): 22-31.

Williams CG, Viljoen JH, van Graan CH and Munro A (1966). The influence of lubrication on the energy cost of pushing a mine car. **Int. Z. angew. Physiol. Einschl. Arbeitphysiol.**, 22: 311-316.

Wyndham CH and Heyns A (1967). Energy expenditures and mechanical efficiencies in pushing a mine-car at various speeds and loads. **European Journal of Applied Physiology**, 24(4): 291-314.

APPENDIX A: HABITUATION AND EXPERIMENTATION

- i) Habituation and Familiarisation Checklist
- ii) Letter of Information
- iii) Informed Consent
- iv) Experimentation Checklist

i) Habituation and Familiarisation Checklist

Equipment

Pallet jack (two different loads of 250 and 500kg)

Data sheets (anthropometric and demographic characteristics)

Anthropometric data

Stadiometer

Toledo Scale

Anthropometer (elbow, shoulder heights)

Procedure

Prior to subject arrival

Subject files ready

Letters of information

Informed consent

Written instructions of Body Discomfort Scale and

Instructions to follow prior to testing

Data sheets for anthropometric and demographic characteristics

Light emitting diode (LED) mirrors and computer set up

After subject arrival

1. Welcome and thank you for participation
2. Letter of information
3. Explanation of aims and objectives, what will be under investigation
4. Explanation of equipment and Body Discomfort scale
5. Information of rules to follow prior to testing (what shoes and clothes to wear; consumption of alcohol, heavy exercise)
6. Informed consent
7. How to start/stop trolley
8. Explanation of protocols
9. Questions and concerns addressed
10. Measurement of stature, mass, elbow and shoulder heights
11. Habituation to use of pallet jack (all three techniques of pushing/pulling) and speed of walking
12. Subject selection of experimentation times

ii) Letter of Information

Dear _____

Thank you for volunteering to partake in my Masters Research Project, entitled:

“THE EFFECT OF PUSH/PULL TECHNIQUE AND LOAD ON SPINAL KINEMATICS, MUSCLE ACTIVITY AND HAND FORCE OUTPUT DURING DYNAMIC PUSHING AND PULLING”

Information pertaining to pushing/pulling is still in its infancy and previous research has failed to definitively identify which of pushing or pulling is preferable to the worker. With these activities occurring more and more frequently and with very little change in injury rates, it is pertinent to establish guidelines to ensure worker safety.

Therefore, the primary objective of this investigation is to determine which of three techniques of dynamic pushing and pulling commonly used in industry evoke the least stress in the human operator from a biomechanical and perceptual perspective, using loads comparable to those transported in industry. By establishing this, I aim to identify the optimal technique, or at least the one which is least harmful to the user for application to the work setting. To achieve this, I will be quantifying spinal motion, hand force production and muscle activity of the upper body. Furthermore, I will be focusing on your own perception of the task in terms of body discomfort to quantify the impact of the task demands and therefore the risk associated with the task.

You will be required to attend two sessions in the Department of Human Kinetics and Ergonomics. The first will be an introductory session, during which testing procedures and protocols will be explicitly explained. At this stage, I will gladly answer any questions that you may have. Once you are completely satisfied that your concerns have been addressed, you are required to sign a consent form, acknowledging your willingness to participate in this investigation. Following this, demographic (age) and anthropometric data (stature, mass, elbow and shoulder heights) will be obtained and you will be afforded the opportunity to familiarize yourself with equipment and testing procedures to ensure that you are comfortable with every aspect of the data collection process.

The next session will involve actual testing and data collection. Prior to testing, you will be reminded of the procedures and use of the Body Discomfort Scale. Six conditions will be investigated; two loads and three push/pull techniques, each of which will be performed until three successful trials have been obtained. You will be pushing/pulling over a distance of 10 metres for all conditions.

During testing, the industrial lumbar motion monitor will be fitted via a harness system on your back and parallel to your spine and electrodes will be attached to specific muscle sites on your torso and dominant arm. This will enable me to monitor and track your spinal movement and muscle activity respectively. During task execution,

you will be exerting hand forces against a load cell, providing information on the forces you are producing. Once a condition is completed, you will be asked to provide a perceptual rating of body discomfort using the Body Discomfort Scale.

Should you have any injuries or be ill at any time of testing, please inform me prior to testing, as this may impact on the validity of your responses and place you at risk of injuring yourself. Please note that you may withdraw from this study at any time if you wish to do so. I sincerely hope that you enjoy participating in this investigation and that it will be an educational experience. Should you have any questions, please do not hesitate to contact me.

Yours sincerely

Sheena Desai
(Masters Student, Department of Human Kinetics and Ergonomics)

iii) Informed Consent

Department of Human Kinetics and Ergonomics

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

“THE EFFECT OF PUSH/PULL TECHNIQUE AND LOAD ON SPINAL KINEMATICS, MUSCLE ACTIVITY AND HAND FORCE OUTPUT DURING DYNAMIC PUSHING AND PULLING”

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

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

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

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

Printed name of Subject

Signed

Date

Printed name of informed consent
Administrator

Signed

Date

Printed name of Witness

Signed

Date

iv) Experimentation Checklist

Equipment

Pallet jack (with two loads of 250 and 500kg)
Lumbar motion monitor (zero-calibration in case, PC, batteries charged)
EMG (electrodes, alcohol, cotton wool, shaving sticks, laptop, batteries charged)
Chatillon (laptop, batteries charged)
Camera (set up, batteries charged)
Body Discomfort scale
Tape measure
Check LEDs
(Water, biscuits, magazines ready for subject)

Prior to subject arrival

1. Subject file ready (data sheets ready with clipboard and pens)
2. Equipment ready
3. Subject files set up on laptops and computers
4. Check testing condition is correct
5. Remind assistants of procedures

After subject arrival

1. Remind subject of use of BD scale
2. Remind subject of how to initiate and end trolley motion
3. Remind subject of speed of walking
4. Shave hair for electrode placement
5. Clean skin with alcohol swab
6. Placement of electrodes, tape down wires
7. Maximum voluntary contractions
8. Placement of Lumbar Motion Monitor (LMM)
9. Individual calibration for LMM

APPENDIX B: DATA COLLECTION

- v) Instructions to Follow Prior to Testing
- vi) Instructions for Use of Body Discomfort Scale
- vii) Body Discomfort Map and Rating Scale (Corlett and Bishop, 1976)
- viii) Demographic and Anthropometric Data
- ix) Data Collection Sheet
- x) Randomisation of Conditions
- xi) Classification of Relative Walking Speeds (Charteris, 1982)
- xii) Maximum Voluntary Contractions (adapted from Kendall **et al.**, 1993)

v) Instructions to Follow Prior to Testing

To ensure accurate results and for standardization purposes, please follow the instructions below **24 hours prior** to testing.

1. DO NOT DRINK ALCOHOL
2. DO NOT PARTAKE IN ANY STRENUOUS EXERCISE
3. MAINTAIN 'NORMAL' HEALTHY EATING

PLEASE REMEMBER TO WEAR A LOOSE VEST OR T-SHIRT AND SHORTS THAT DO NOT RESTRICT MOVEMENT DURING TESTING. PLEASE ARRIVE AT YOUR TESTING SESSION WEARING SOCKS AND TRAINING SHOES WITH RUBBER SOLES.

If you fail to comply with any of the above regulations, please inform the researcher before testing commences.

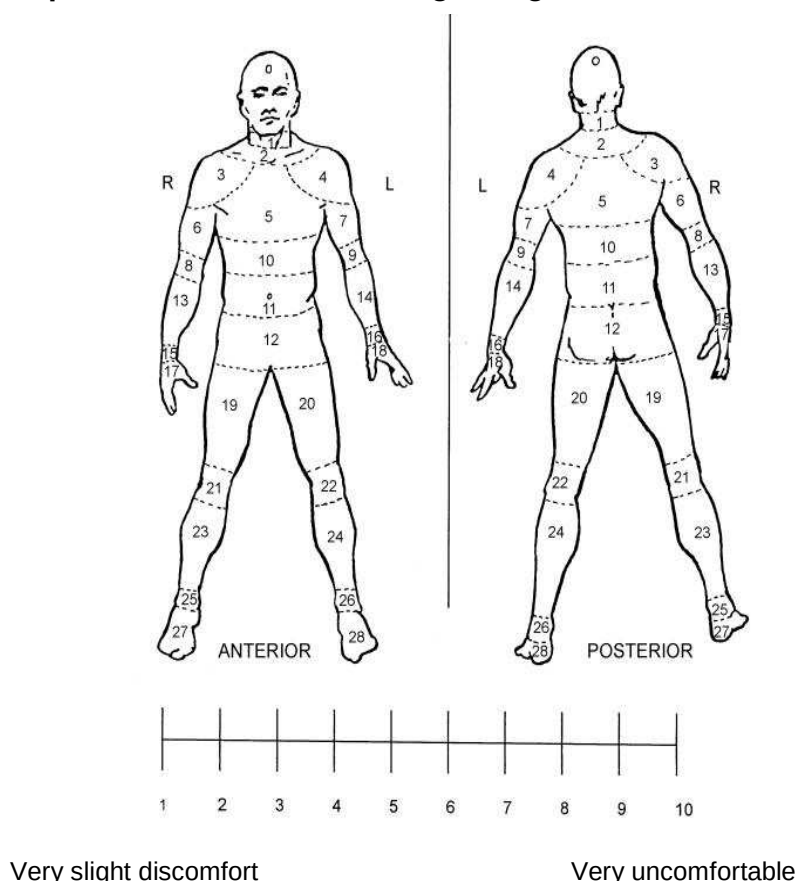
vi) Instructions for Use of Body Discomfort Scale

BODY DISCOMFORT

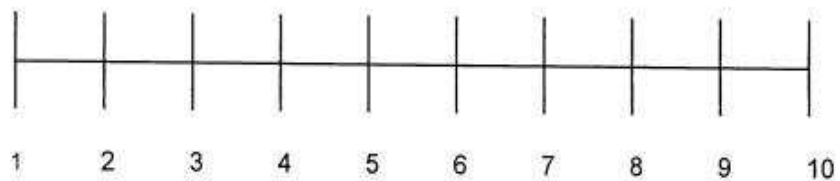
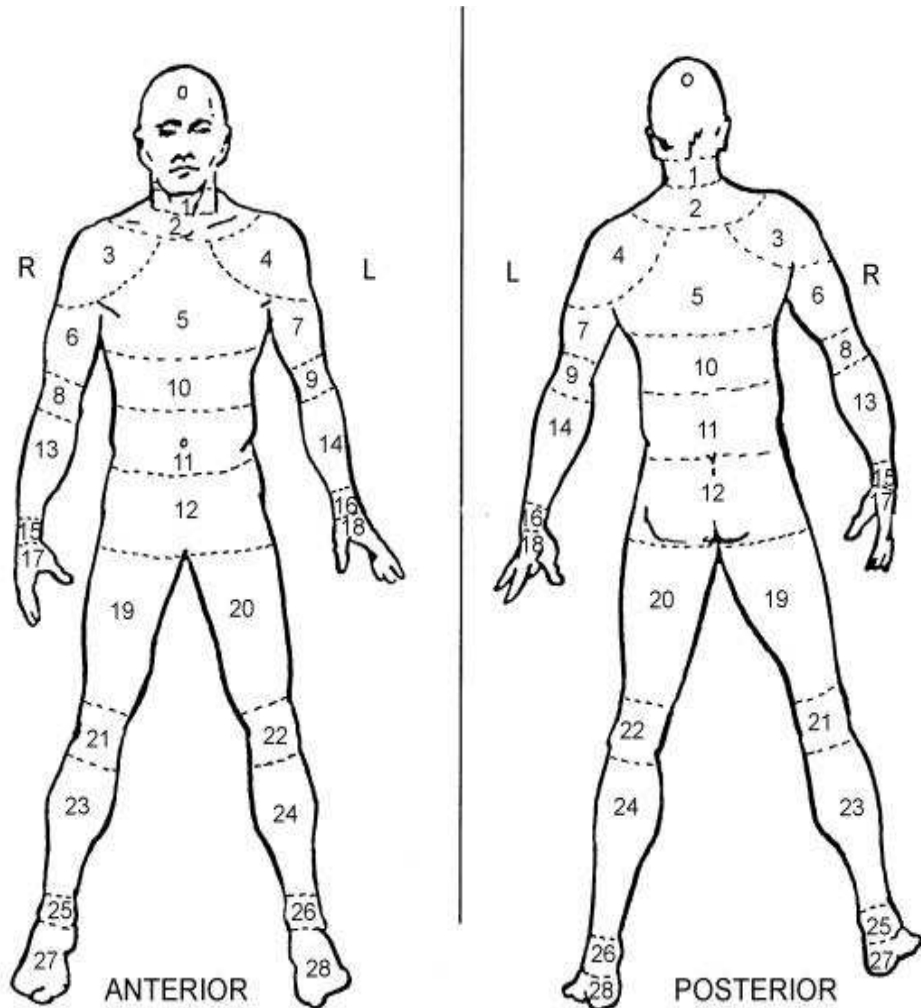
After completing each *condition* (3 successful pushes or pulls), you will be asked to identify the exact areas of the body in which you experienced discomfort while pushing or pulling using the *Body Discomfort Map* (shown below). It is divided into two body maps, each of which is divided into 29 segments, numbered from 0 to 28. One map indicates the anterior (front) of the body, the other the posterior (back). On presentation of the body discomfort maps, you will select *one or more* body segment(s) by pointing to the appropriate side of the body (front or back) and selecting the appropriate body region(s). Following this, please rate the corresponding intensity of discomfort on a scale ranging from 1 to 10, with 1 indicating “minimal discomfort” (only very slight discomfort) and 10 “maximal discomfort” (extremely uncomfortable).

To ensure valid results, it is necessary that you **be as honest as possible** when using these scales.

If you require further instruction regarding these scales, do not hesitate to ask.



vii) Body Discomfort Map and Rating Scale
(Corlett and Bishop, 1976)



Very slight discomfort

Very uncomfortable

viii) Demographic and Anthropometric Data

Name	
<i>Subject code</i>	
<i>Date of Birth</i>	
<i>Age</i>	
<i>Stature (mm)</i>	
<i>Mass (kg)</i>	
<i>Elbow height (mm)</i>	
<i>Shoulder height (mm)</i>	
<i>Hand dominance</i>	
<i>Condition sequence</i>	

ix) Data Collection Sheet

Subject code _____

Date _____

Condition sequence _____

Condition _____

Distance (mm): CM to handle interface (initial)	
Distance (mm): CM to handle interface (ending)	

EMG						Speed st.s ⁻¹
Trial	Good trial (tick)	Start		End		
		Time	Marker	Time	Marker	
1						
2						
3						
4						
5						
6						

Comments _____ _____ _____ _____ _____ _____ _____	Body discomfort	
	Site	Rating

x) Randomisation of Conditions

Subject

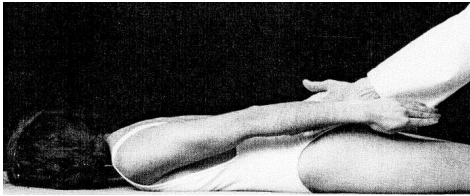
1	1	2	3	4	5	6
2	1	2	5	4	3	6
3	1	4	3	2	5	6
4	1	4	5	2	3	6
5	1	6	3	2	5	4
6	1	6	5	2	3	4
7	2	1	4	3	6	5
8	2	1	6	3	4	5
9	2	3	4	1	6	5
10	2	3	6	1	4	5
11	2	5	4	1	6	3
12	2	5	6	1	4	3
13	3	2	1	6	5	4
14	3	2	5	6	1	4
15	3	4	1	6	5	2
16	3	4	5	6	1	2
17	3	6	1	4	5	2
18	3	6	5	4	1	2
19	4	1	2	3	6	5
20	4	1	6	3	2	5
21	4	3	2	5	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

xi) Classification of Relative Walking Speeds
(Charteris, 1982)

Relative speed (R.Sp) (st.s⁻¹)	Description
Up to 0.3	Very slow
0.4-0.6	Slow
0.7	Slow-medium
0.8-1.0	Medium
1.1	Medium-fast
1.2-1.4	Fast
1.5 and above	Very fast

xii) Maximum Voluntary Contractions (adapted from Kendall **et al.**, 1993)

	Brachioradialis Participant flexes the elbow with the forearm neutral between pronation and supination as the researcher applies pressure in the direction of extension, while supporting the elbow.
	Triceps brachii Participant lies supine, with shoulder flexed at about 90° and extends the elbow (to slightly less than full extension) as the researcher applies pressure in the direction of flexion, while supporting the arm in a position perpendicular to the table..
	Anterior deltoid Participant sits, with shoulder abducted and in slight flexion and with the humerus in slight lateral rotation, while the researcher applies pressure against the anteromedial surface of the arm in the direction of adduction and slight extension.
	Medial deltoid Participant sits, with shoulder abducted but not rotated and the elbow flexed to indicate the neutral position of rotation, while the researcher applies pressure against the dorsal surface of the distal end of the humerus.

	Posterior deltoid Participant sits, with shoulder abducted and in slight extension and the humerus in slight medial rotation, while the researcher applies pressure against the posterolateral surface of the arm above the elbow in the direction of adduction and slight flexion.
	Trapezius Participant sits, with acromiale end of the clavicle and scapula elevated, the neck in posterolateral extension bringing the occiput toward the elevated shoulder with the face turned in the opposite direction, while the researcher applies pressure against the shoulder in the direction of depression, and against the head in the direction of flexion anterolaterally.
	Latissimus dorsi Participant lies prone with the arm in adduction, with extension in the medially rotated position, while the researcher applies pressure in the direction of abduction and slight flexion of the arm.
	Erector spinae Participant lies prone with hands clasped behind the head, while the researcher stabilises the legs firmly on the table. In this position, the participant performs trunk extension to the full range of motion.

APPENDIX C: SUMMARY REPORTS

xiii) ANOVA Tables:

Hand Forces

Initial versus Sustained versus Ending Forces

Spinal Kinematics

Muscle Activity

xiv) Lower Back Disorder Risk Model

xv) Selection of Muscles

xvi) Symmetry of Muscle Activity on the Left and Right Sides of the Body

xiii) ANOVA Tables

Hand Forces

Tukey HSD test; variable Initial force Approximate Probabilities for Post Hoc Tests Error: Between MS = 1688.2, df = 210.00								
	Technique	Load	{1} - 198.36	{2} - 327.23	{3} - 191.78	{4} - 303.17	{5} - 173.44	{6} - 294.22
1	2 push	250 kg		0.000020	0.984268	0.000020	0.104095	0.000020
2	2 push	500 kg	0.000020		0.000020	0.128667	0.000020	0.008596
3	2 pull	250 kg	0.984268	0.000020		0.000020	0.406343	0.000020
4	2 pull	500 kg	0.000020	0.128667	0.000020		0.000020	0.940591
5	1 pull	250 kg	0.104095	0.000020	0.406343	0.000020		0.000020
6	1 pull	500 kg	0.000020	0.008596	0.000020	0.940591	0.000020	

Tukey HSD test; variable Sustained force Approximate Probabilities for Post Hoc Tests Error: Between MS = 147.98, df = 210.00								
	Technique	Load	{1} - 46.450	{2} - 111.28	{3} - 42.686	{4} - 102.80	{5} - 40.800	{6} - 103.43
1	2 push	250 kg		0.000020	0.778121	0.000020	0.359337	0.000020
2	2 push	500 kg	0.000020		0.000020	0.036567	0.000020	0.067762
3	2 pull	250 kg	0.778121	0.000020		0.000020	0.986391	0.000020
4	2 pull	500 kg	0.000020	0.036567	0.000020		0.000020	0.999931
5	1 pull	250 kg	0.359337	0.000020	0.986391	0.000020		0.000020
6	1 pull	500 kg	0.000020	0.067762	0.000020	0.999931	0.000020	

Tukey HSD test; variable Ending force Approximate Probabilities for Post Hoc Tests Error: Between MS = 2901.7, df = 210.00								
	Technique	Load	{1} - -104.0	{2} - -159.5	{3} - -98.63	{4} - -160.9	{5} - -113.3	{6} - -178.3
1	2 push	250 kg		0.000190	0.998322	0.000124	0.977470	0.000020
2	2 push	500 kg	0.000190		0.000042	0.999998	0.003706	0.678376
3	2 pull	250 kg	0.998322	0.000042		0.000033	0.857102	0.000020
4	2 pull	500 kg	0.000124	0.999998	0.000033		0.002498	0.742654
5	1 pull	250 kg	0.977470	0.003706	0.857102	0.002498		0.000024
6	1 pull	500 kg	0.000020	0.678376	0.000020	0.742654	0.000024	

Initial versus Sustained versus Ending Forces

Tukey HSD test; variable Con1 (Spreadsheet2) Approximate Probabilities for Post Hoc Tests Error:
Between MS = 932.39, df = 105.00

	Phase	{1} - 198.36	{2} - 46.450	{3} - 103.97
1	initial		0.000104	0.000104
2	sustained	0.000104		0.000104
3	ending	0.000104	0.000104	

Tukey HSD test; variable Con2 (Spreadsheet2) Approximate Probabilities for Post Hoc Tests Error:
Between MS = 2552.7, df = 105.00

	Phase	{1} - 327.23	{2} - 111.28	{3} - 159.54
1	initial		0.000104	0.000104
2	sustained	0.000104		0.000380
3	ending	0.000104	0.000380	

Tukey HSD test; variable Con3 (Spreadsheet2) Approximate Probabilities for Post Hoc Tests Error:
Between MS = 782.70, df = 105.00

	Phase	{1} - 191.78	{2} - 42.686	{3} - 98.625
1	initial		0.000104	0.000104
2	sustained	0.000104		0.000104
3	ending	0.000104	0.000104	

Tukey HSD test; variable Con4 (Spreadsheet2) Approximate Probabilities for Post Hoc Tests Error:
Between MS = 2361.1, df = 105.00

	Phase	{1} - 303.17	{2} - 102.80	{3} - 160.86
1	initial		0.000104	0.000104
2	sustained	0.000104		0.000108
3	ending	0.000104	0.000108	

Tukey HSD test; variable Con5 (Spreadsheet2) Approximate Probabilities for Post Hoc Tests Error:
Between MS = 925.57, df = 105.00

	Phase	{1} - 173.44	{2} - 40.800	{3} - 113.32
1	initial		0.000104	0.000104
2	sustained	0.000104		0.000104
3	ending	0.000104	0.000104	

Tukey HSD test; variable Con6 (Spreadsheet2) Approximate Probabilities for Post Hoc Tests Error:
Between MS = 1921.3, df = 105.00

	Phase	{1} - 294.22	{2} - 103.43	{3} - 178.31
1	initial		0.000104	0.000104
2	sustained	0.000104		0.000104
3	ending	0.000104	0.000104	

Spinal Kinematics

Tukey HSD test; variable Sagittal position Approximate Probabilities for Post Hoc Tests Error: Between MS = 31.738, df = 210.00								
	Technique	Load	{1} - 9.9259	{2} - 10.903	{3} - 13.046	{4} - 17.438	{5} - 10.931	{6} - 13.649
1	2 push	250 kg		0.977496	0.174395	0.000020	0.974509	0.056867
2	2 push	500 kg	0.977496		0.589411	0.000032	1.000000	0.304373
3	2 pull	250 kg	0.174395	0.589411		0.012119	0.603485	0.997591
4	2 pull	500 kg	0.000020	0.000032	0.012119		0.000033	0.049476
5	1 pull	250 kg	0.974509	1.000000	0.603485	0.000033		0.315924
6	1 pull	500 kg	0.056867	0.304373	0.997591	0.049476	0.315924	

Tukey HSD test; variable Lateral position Approximate Probabilities for Post Hoc Tests Error: Between MS = 9.0113, df = 210.00								
	Technique	Load	{1} - .99249	{2} - 1.0742	{3} - 1.3518	{4} - 1.4663	{5} - -2.281	{6} - .04331
1	2 push	250 kg		0.999997	0.995899	0.985252	0.000072	0.761779
2	2 push	500 kg	0.999997		0.998806	0.993824	0.000049	0.691768
3	2 pull	250 kg	0.995899	0.998806		0.999985	0.000024	0.433910
4	2 pull	500 kg	0.985252	0.993824	0.999985		0.000022	0.335822
5	1 pull	250 kg	0.000072	0.000049	0.000024	0.000022		0.013072
6	1 pull	500 kg	0.761779	0.691768	0.433910	0.335822	0.013072	

Tukey HSD test; variable Twist position Approximate Probabilities for Post Hoc Tests Error: Between MS = 24.322, df = 210.00								
	Technique	Load	{1} - -1.256	{2} - -.9699	{3} - -.7268	{4} - -.9858	{5} - 18.687	{6} - 16.688
1	2 push	250 kg		0.999878	0.997556	0.999908	0.000020	0.000020
2	2 push	500 kg	0.999878		0.999945	1.000000	0.000020	0.000020
3	2 pull	250 kg	0.997556	0.999945		0.999925	0.000020	0.000020
4	2 pull	500 kg	0.999908	1.000000	0.999925		0.000020	0.000020
5	1 pull	250 kg	0.000020	0.000020	0.000020	0.000020		0.518921
6	1 pull	500 kg	0.000020	0.000020	0.000020	0.000020	0.518921	

Tukey HSD test; variable Maximum sagittal range Approximate Probabilities for Post Hoc Tests								
Error: Between MS = 14.240, df = 210.00								
	Technique	Load	{1} - 9.4270	{2} - 13.192	{3} - 12.587	{4} - 17.960	{5} - 12.638	{6} - 15.926
1	2 push	250 kg		0.000344	0.005138	0.000020	0.004175	0.000020
2	2 push	500 kg	0.000344		0.984121	0.000021	0.989306	0.025827
3	2 pull	250 kg	0.005138	0.984121		0.000020	1.000000	0.002409
4	2 pull	500 kg	0.000020	0.000021	0.000020		0.000020	0.199090
5	1 pull	250 kg	0.004175	0.989306	1.000000	0.000020		0.002993
6	1 pull	500 kg	0.000020	0.025827	0.002409	0.199090	0.002993	

Tukey HSD test; variable Maximum lateral range Approximate Probabilities for Post Hoc Tests								
Error: Between MS = 11.742, df = 210.00								
	Technique	Load	{1} - 9.1265	{2} - 11.184	{3} - 8.3122	{4} - 9.2825	{5} - 14.814	{6} - 19.419
1	2 push	250 kg		0.110462	0.915425	0.999963	0.000020	0.000020
2	2 push	500 kg	0.110462		0.005072	0.172424	0.000118	0.000020
3	2 pull	250 kg	0.915425	0.005072		0.836432	0.000020	0.000020
4	2 pull	500 kg	0.999963	0.172424	0.836432		0.000020	0.000020
5	1 pull	250 kg	0.000020	0.000118	0.000020	0.000020		0.000020
6	1 pull	500 kg	0.000020	0.000020	0.000020	0.000020	0.000020	

Tukey HSD test; variable Maximum twisting angle Approximate Probabilities for Post Hoc Tests								
Error: Between MS = 34.338, df = 210.00								
	Technique	Load	{1} - 17.057	{2} - 20.174	{3} - 13.341	{4} - 14.529	{5} - 35.274	{6} - 37.735
1	2 push	250 kg		0.212044	0.077110	0.446162	0.000020	0.000020
2	2 push	500 kg	0.212044		0.000030	0.000633	0.000020	0.000020
3	2 pull	250 kg	0.077110	0.000030		0.955811	0.000020	0.000020
4	2 pull	500 kg	0.446162	0.000633	0.955811		0.000020	0.000020
5	1 pull	250 kg	0.000020	0.000020	0.000020	0.000020		0.477701
6	1 pull	500 kg	0.000020	0.000020	0.000020	0.000020	0.477701	

Tukey HSD test; variable Maximum sagittal velocity Approximate Probabilities for Post Hoc Tests
Error: Between MS = 40.082, df = 210.00

	Technique	Load	{1} - 17.047	{2} - 23.164	{3} - 20.848	{4} - 25.139	{5} - 20.543	{6} - 25.859
1	2 push	250 kg		0.000603	0.110725	0.000021	0.177103	0.000020
2	2 push	500 kg	0.000603		0.630470	0.771820	0.494285	0.461524
3	2 pull	250 kg	0.110725	0.630470		0.046447	0.999951	0.010202
4	2 pull	500 kg	0.000021	0.771820	0.046447		0.025262	0.996782
5	1 pull	250 kg	0.177103	0.494285	0.999951	0.025262		0.004954
6	1 pull	500 kg	0.000020	0.461524	0.010202	0.996782	0.004954	

Tukey HSD test; variable Maximum lateral velocity Approximate Probabilities for Post Hoc Tests
Error: Between MS = 58.799, df = 210.00

	Technique	Load	{1} - 25.301	{2} - 28.349	{3} - 21.330	{4} - 20.961	{5} - 29.068	{6} - 33.123
1	2 push	250 kg		0.540778	0.238794	0.155569	0.295485	0.000232
2	2 push	500 kg	0.540778		0.001446	0.000631	0.998723	0.087587
3	2 pull	250 kg	0.238794	0.001446		0.999952	0.000281	0.000020
4	2 pull	500 kg	0.155569	0.000631	0.999952		0.000122	0.000020
5	1 pull	250 kg	0.295485	0.998723	0.000281	0.000122		0.217921
6	1 pull	500 kg	0.000232	0.087587	0.000020	0.000020	0.217921	

Tukey HSD test; variable Maximum twist velocity Approximate Probabilities for Post Hoc Tests
Error: Between MS = 104.84, df = 210.00

	Technique	Load	{1} - 39.176	{2} - 43.983	{3} - 30.583	{4} - 30.125	{5} - 58.139	{6} - 57.851
1	2 push	250 kg		0.347019	0.004996	0.002441	0.000020	0.000020
2	2 push	500 kg	0.347019		0.000021	0.000020	0.000020	0.000020
3	2 pull	250 kg	0.004996	0.000021		0.999966	0.000020	0.000020
4	2 pull	500 kg	0.002441	0.000020	0.999966		0.000020	0.000020
5	1 pull	250 kg	0.000020	0.000020	0.000020	0.000020		0.999997
6	1 pull	500 kg	0.000020	0.000020	0.000020	0.000020	0.999997	

Tukey HSD test; variable Maximum sagittal acceleration Approximate Probabilities for Post Hoc Tests Error: Between MS = 2406.6, df = 210.00								
	Technique	Load	{1} - 125.89	{2} - 175.40	{3} - 162.46	{4} - 177.99	{5} - 141.34	{6} - 187.17
1	2 push	250 kg		0.000281	0.019489	0.000113	0.764850	0.000022
2	2 push	500 kg	0.000281		0.873557	0.999923	0.037918	0.912282
3	2 pull	250 kg	0.019489	0.873557		0.760751	0.448498	0.268185
4	2 pull	500 kg	0.000113	0.999923	0.760751		0.019050	0.968694
5	1 pull	250 kg	0.764850	0.037918	0.448498	0.019050		0.001051
6	1 pull	500 kg	0.000022	0.912282	0.268185	0.968694	0.001051	

Tukey HSD test; variable Maximum lateral acceleration Approximate Probabilities for Post Hoc Tests Error: Between MS = 3004.1, df = 210.00								
	Technique	Load	{1} - 193.78	{2} - 206.07	{3} - 172.44	{4} - 163.54	{5} - 218.88	{6} - 245.19
1	2 push	250 kg		0.932944	0.563927	0.177670	0.375971	0.000986
2	2 push	500 kg	0.932944		0.096403	0.012745	0.920902	0.029682
3	2 pull	250 kg	0.563927	0.096403		0.983201	0.004411	0.000021
4	2 pull	500 kg	0.177670	0.012745	0.983201		0.000279	0.000020
5	1 pull	250 kg	0.375971	0.920902	0.004411	0.000279		0.321496
6	1 pull	500 kg	0.000986	0.029682	0.000021	0.000020	0.321496	

Tukey HSD test; variable Maximum twist acceleration Approximate Probabilities for Post Hoc Tests Error: Between MS = 4709.8, df = 210.00								
	Technique	Load	{1} - 297.21	{2} - 322.14	{3} - 239.80	{4} - 221.61	{5} - 362.20	{6} - 393.84
1	2 push	250 kg		0.637296	0.005210	0.000061	0.000842	0.000020
2	2 push	500 kg	0.637296		0.000025	0.000020	0.131052	0.000151
3	2 pull	250 kg	0.005210	0.000025		0.871394	0.000020	0.000020
4	2 pull	500 kg	0.000061	0.000020	0.871394		0.000020	0.000020
5	1 pull	250 kg	0.000842	0.131052	0.000020	0.000020		0.368053
6	1 pull	500 kg	0.000020	0.000151	0.000020	0.000020	0.368053	

Muscle Activity

Tukey HSD test; variable Brachioradialis Approximate Probabilities for Post Hoc Tests Error: Between MS = .59445, df = 210.00								
	Technique	Load	{1} - 1.0536	{2} - 1.6089	{3} - .76321	{4} - 1.0546	{5} - 2.0144	{6} - 2.3619
1	2 push	250 kg		0.027301	0.599721	1.000000	0.000022	0.000020
2	2 push	500 kg	0.027301		0.000065	0.027720	0.223125	0.000500
3	2 pull	250 kg	0.599721	0.000065		0.596413	0.000020	0.000020
4	2 pull	500 kg	1.000000	0.027720	0.596413		0.000022	0.000020
5	1 pull	250 kg	0.000022	0.223125	0.000020	0.000022		0.394411
6	1 pull	500 kg	0.000020	0.000500	0.000020	0.000020	0.394411	

Tukey HSD test; variable Triceps brachii Approximate Probabilities for Post Hoc Tests Error: Between MS = .31127, df = 210.00								
	Technique	Load	{1} - 1.9939	{2} - 2.2696	{3} - 1.9972	{4} - 2.4540	{5} - 1.4916	{6} - 2.2525
1	2 push	250 kg		0.289086	1.000000	0.006237	0.001867	0.361570
2	2 push	500 kg	0.289086		0.302649	0.725552	0.000020	0.999995
3	2 pull	250 kg	1.000000	0.302649		0.006828	0.001689	0.376765
4	2 pull	500 kg	0.006237	0.725552	0.006828		0.000020	0.643437
5	1 pull	250 kg	0.001867	0.000020	0.001689	0.000020		0.000020
6	1 pull	500 kg	0.361570	0.999995	0.376765	0.643437	0.000020	

Tukey HSD test; variable Anterior deltoid Approximate Probabilities for Post Hoc Tests Error: Between MS = .43175, df = 210.00								
	Technique	Load	{1} - 1.7913	{2} - 2.9708	{3} - .75812	{4} - 1.0825	{5} - 1.2069	{6} - 1.7263
1	2 push	250 kg		0.000020	0.000020	0.000086	0.002230	0.998337
2	2 push	500 kg	0.000020		0.000020	0.000020	0.000020	0.000020
3	2 pull	250 kg	0.000020	0.000020		0.290134	0.043651	0.000020
4	2 pull	500 kg	0.000086	0.000020	0.290134		0.967036	0.000474
5	1 pull	250 kg	0.002230	0.000020	0.043651	0.967036		0.010363
6	1 pull	500 kg	0.998337	0.000020	0.000020	0.000474	0.010363	

Tukey HSD test; variable Medial deltoid Approximate Probabilities for Post Hoc Tests Error: Between MS = .37984, df = 210.00								
	Technique	Load	{1} - 1.1325	{2} - 2.0954	{3} - .53618	{4} - .74337	{5} - 1.0856	{6} - 1.1698
1	2 push	250 kg		0.000020	0.000587	0.079442	0.999536	0.999849
2	2 push	500 kg	0.000020		0.000020	0.000020	0.000020	0.000020
3	2 pull	250 kg	0.000587	0.000020		0.710981	0.002157	0.000201
4	2 pull	500 kg	0.079442	0.000020	0.710981		0.171998	0.039060
5	1 pull	250 kg	0.999536	0.000020	0.002157	0.171998		0.992376
6	1 pull	500 kg	0.999849	0.000020	0.000201	0.039060	0.992376	

Tukey HSD test; variable Posterior deltoid Approximate Probabilities for Post Hoc Tests Error: Between MS = .33232, df = 210.00								
	Technique	Load	{1} - 1.3634	{2} - 1.8196	{3} - 1.4931	{4} - 2.0898	{5} - 1.9082	{6} - 2.3606
1	2 push	250 kg		0.010247	0.932103	0.000021	0.000873	0.000020
2	2 push	500 kg	0.010247		0.155195	0.348662	0.986918	0.000977
3	2 pull	250 kg	0.932103	0.155195		0.000178	0.027340	0.000020
4	2 pull	500 kg	0.000021	0.348662	0.000178		0.764547	0.346457
5	1 pull	250 kg	0.000873	0.986918	0.027340	0.764547		0.011257
6	1 pull	500 kg	0.000020	0.000977	0.000020	0.346457	0.011257	

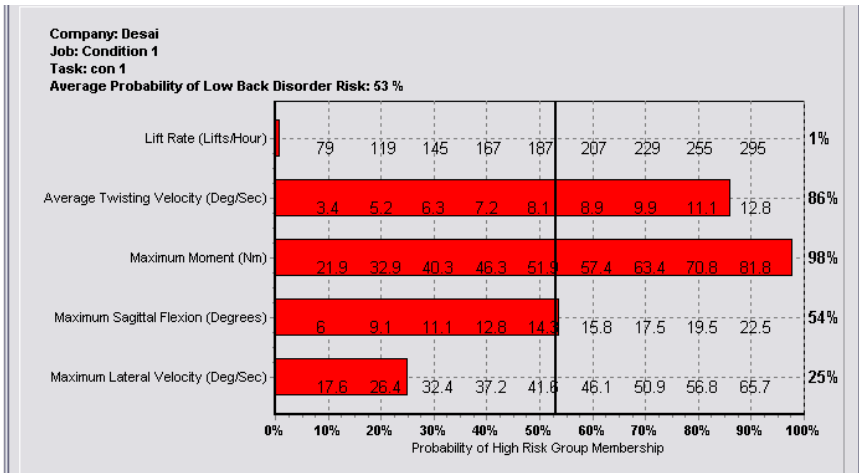
Tukey HSD test; variable Trapezius Approximate Probabilities for Post Hoc Tests Error: Between MS = .35263, df = 210.00								
	Technique	Load	{1} - 1.1083	{2} - 1.9621	{3} - .64843	{4} - .90919	{5} - 2.1424	{6} - 2.4194
1	2 push	250 kg		0.000020	0.013037	0.713201	0.000020	0.000020
2	2 push	500 kg	0.000020		0.000020	0.000020	0.791715	0.013859
3	2 pull	250 kg	0.013037	0.000020		0.425229	0.000020	0.000020
4	2 pull	500 kg	0.713201	0.000020	0.425229		0.000020	0.000020
5	1 pull	250 kg	0.000020	0.791715	0.000020	0.000020		0.354290
6	1 pull	500 kg	0.000020	0.013859	0.000020	0.000020	0.354290	

Tukey HSD test; variable Latissimus dorsi Approximate Probabilities for Post Hoc Tests Error: Between MS = .22368, df = 210.00								
	Technique	Load	{1} - 1.2638	{2} - 1.7064	{3} - 1.3770	{4} - 1.8836	{5} - 1.7541	{6} - 2.2868
1	2 push	250 kg		0.001023	0.912960	0.000021	0.000173	0.000020
2	2 push	500 kg	0.001023		0.036960	0.605200	0.998170	0.000023
3	2 pull	250 kg	0.912960	0.036960		0.000097	0.009364	0.000020
4	2 pull	500 kg	0.000021	0.605200	0.000097		0.855191	0.004051
5	1 pull	250 kg	0.000173	0.998170	0.009364	0.855191		0.000044
6	1 pull	500 kg	0.000020	0.000023	0.000020	0.004051	0.000044	

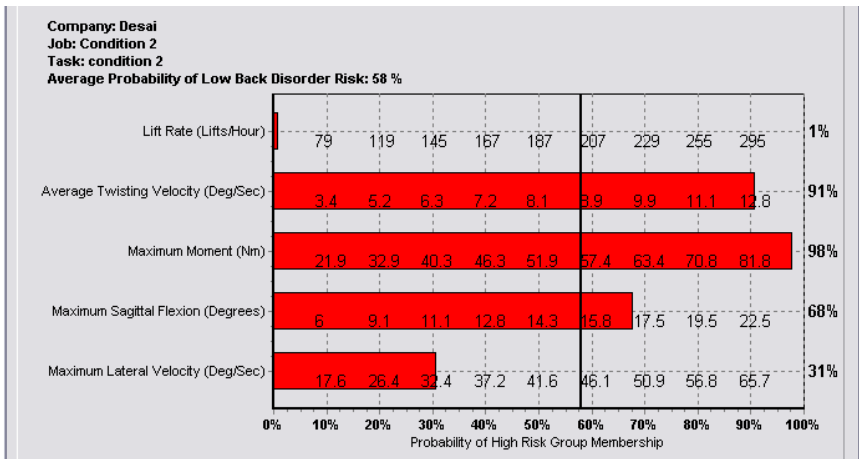
Tukey HSD test; variable Erector spinae Approximate Probabilities for Post Hoc Tests Error: Between MS = .35338, df = 210.00								
	Technique	Load	{1} - 2.4684	{2} - 2.7691	{3} - 2.6556	{4} - 2.9488	{5} - 2.4852	{6} - 2.6047
1	2 push	250 kg		0.263794	0.764812	0.008003	0.999997	0.926659
2	2 push	500 kg	0.263794		0.965908	0.794684	0.327268	0.849867
3	2 pull	250 kg	0.764812	0.965908		0.291279	0.828881	0.999174
4	2 pull	500 kg	0.008003	0.794684	0.291279		0.012061	0.137552
5	1 pull	250 kg	0.999997	0.327268	0.828881	0.012061		0.957312
6	1 pull	500 kg	0.926659	0.849867	0.999174	0.137552	0.957312	

xiv) Low Back Disorder Risk Model

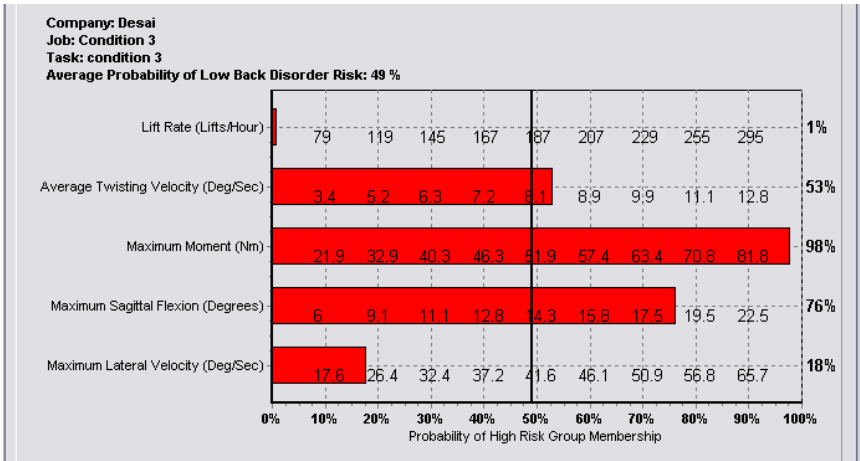
Lower back disorder risk for pushing with 250kg



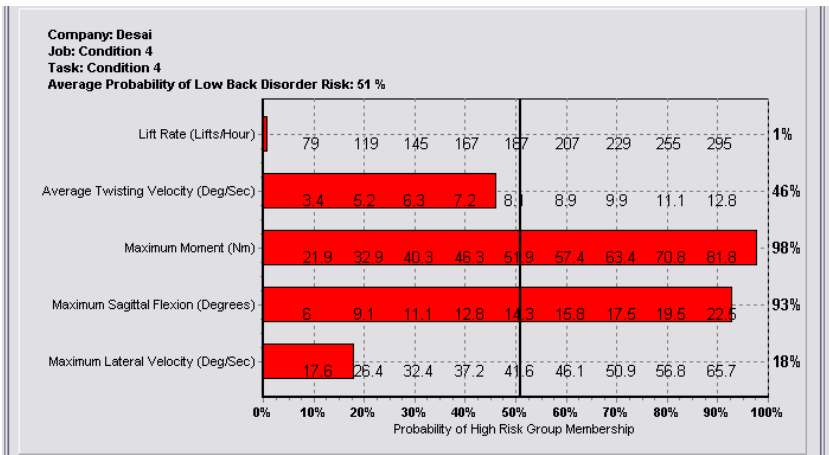
Lower back disorder risk for pushing with 500kg



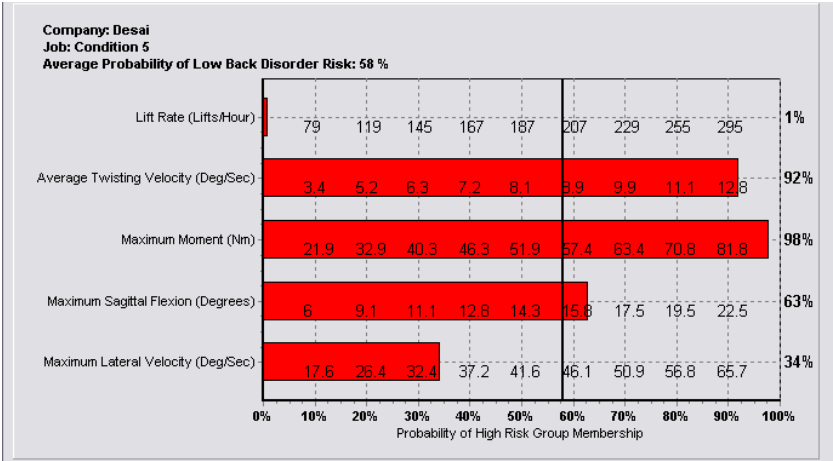
Lower back disorder risk for two-handed pulling with 250kg



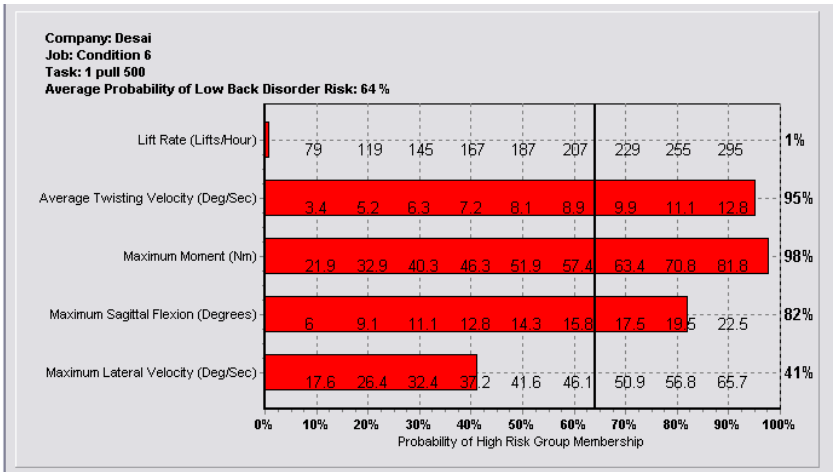
Lower back disorder risk for two-handed pulling with 500kg



Lower back disorder risk for one-handed pulling with 250kg



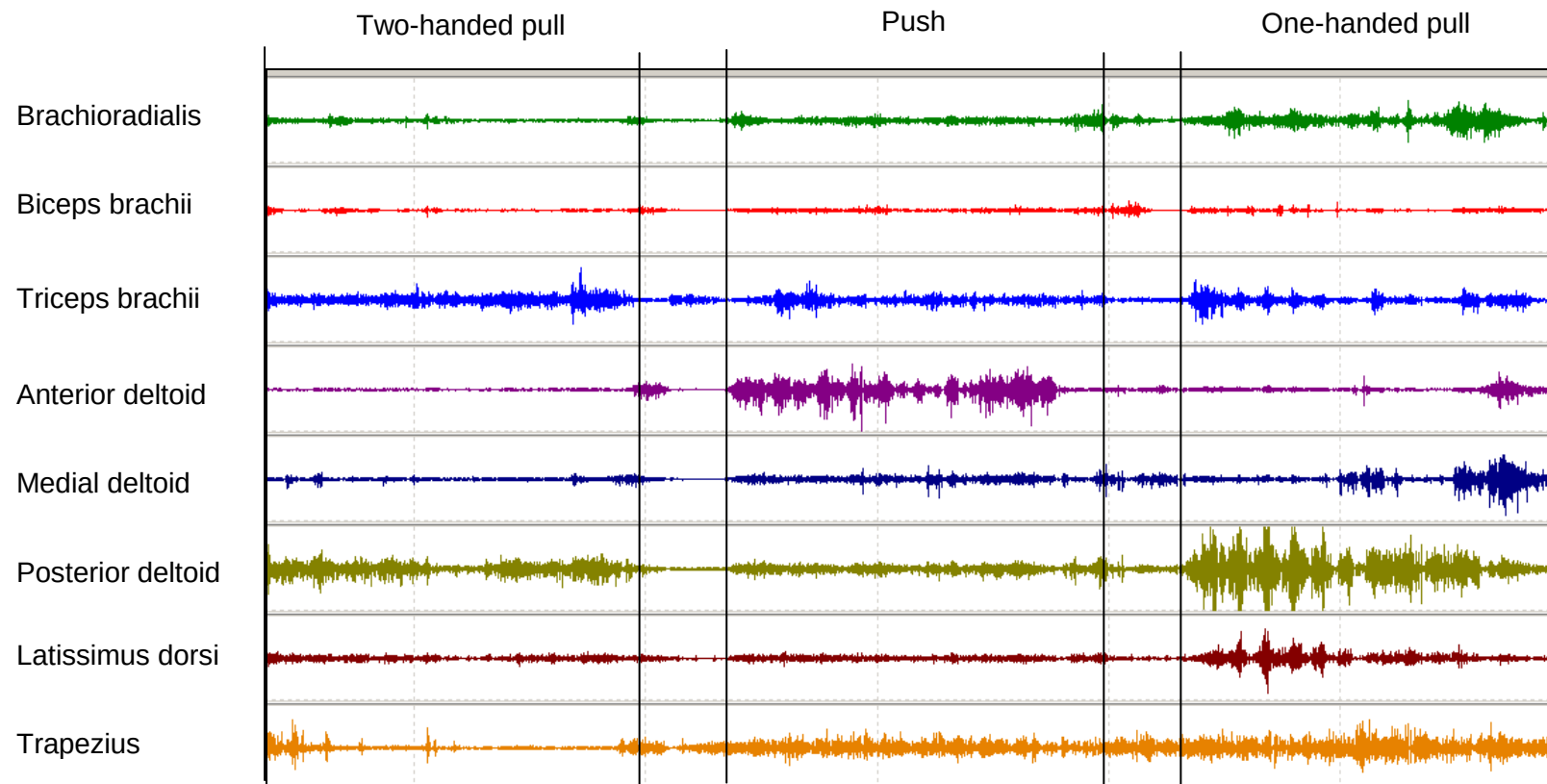
Lower back disorder risk for one-handed pulling with 500kg



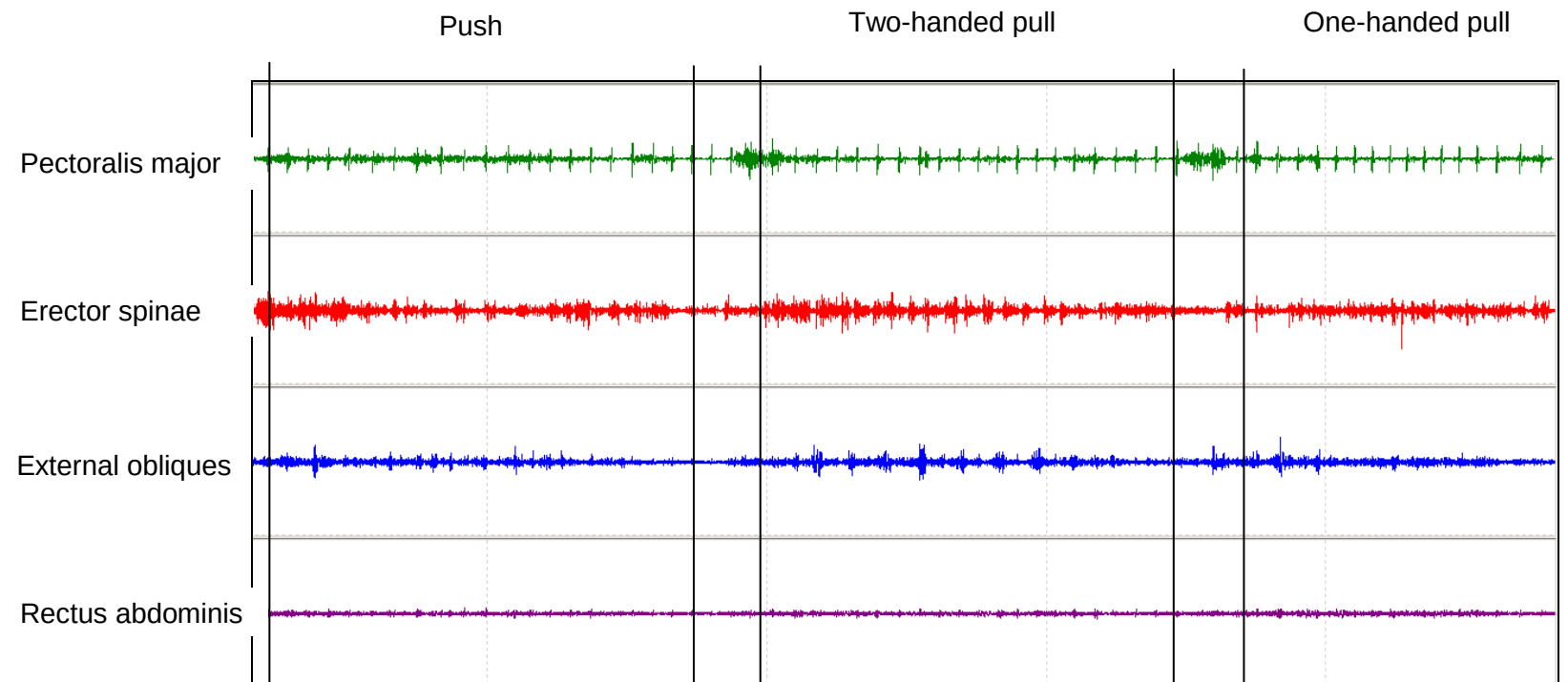
xv) Selection of Muscles

Figures a) and b) indicate differences between activation levels for various muscles evaluated during pilot testing, while individuals performed the three push/pull techniques at 500kg. The muscles eliciting the highest activation levels were chosen for experimentation.

a)



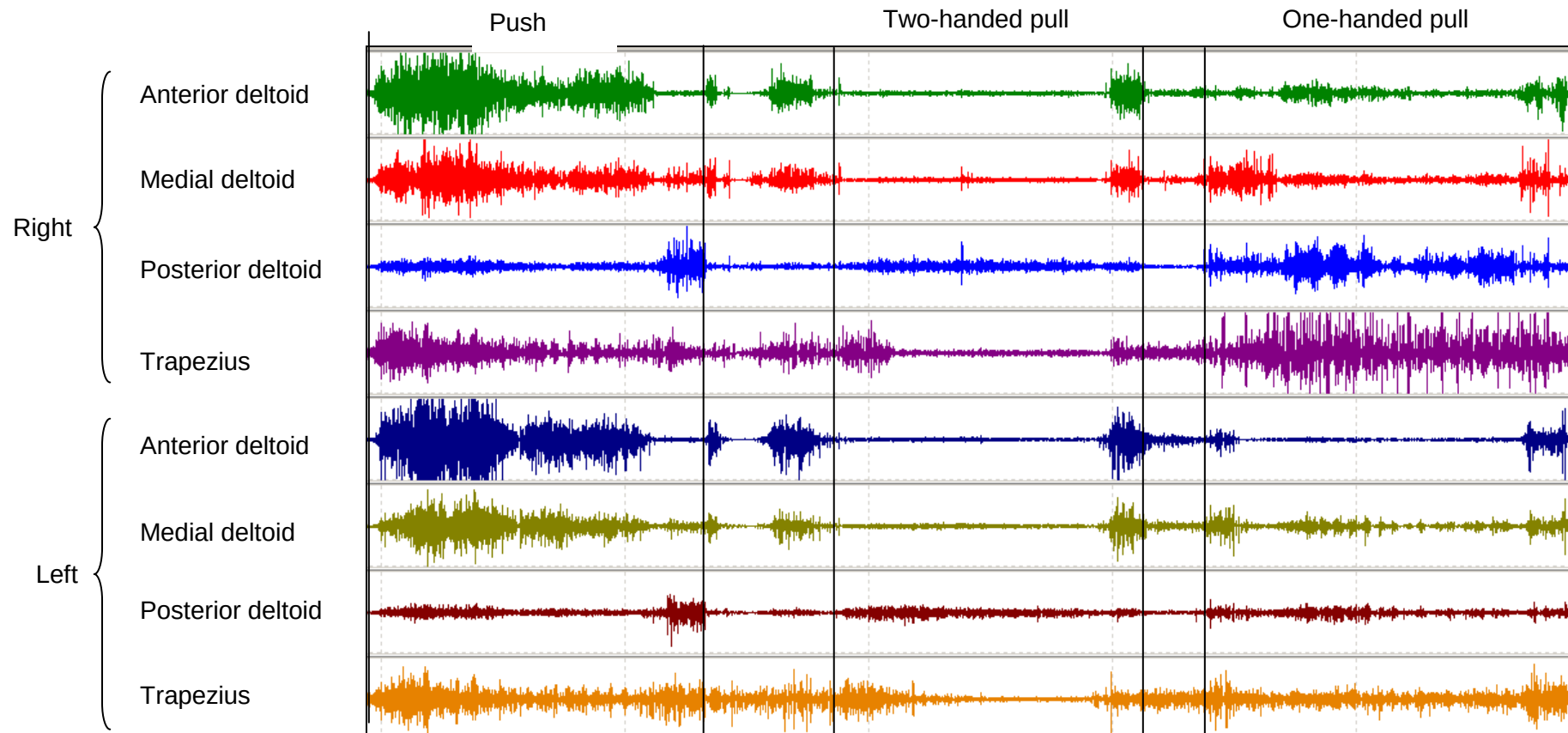
b)



xvi) Symmetry of Muscle Activity on the Left and Right Sides of the Body

Figures c) and d) indicate muscle activity for different muscles on both the left and right sides of the body. During pilot testing, it was found that for the bilateral techniques, the right and left sides were equally active, and for the unilateral technique the right side was most active. Therefore, muscles on the right side of the body were assessed during experimentation.

c)



d)

