FIELD AND LABORATORY ANALYSES OF MANUAL TASKS IN THE SOUTH AFRICAN AUTOMOTIVE INDUSTRY

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ABSTRACT

The present study adopted a “field-laboratory-field” approach in the assessment of the efficacy of ergonomics interventions specific to two selected tasks evaluated in a South African automotive industry.

Initial field testing was conducted in an Eastern Cape (South Africa) automotive plant where high risk areas were identified during walkthrough ergonomics surveys in conjunction with interaction with operators. Temporal factors and working postures of 12 industrial workers were recorded and observed, while physiological and perceptual responses were assessed. Two priority areas were focused upon for analysis, namely the Paintshop and Bodyshop with the former identified as being the more taxing of the two tasks. Responses of 30 students participating in rigourously controlled laboratory simulations were subsequently collected while completing the two tasks, namely the Paintshop Trolley Transfer (PTT) and Car Door Carriage (CDC) for participants. Working postures, kinematic, physiological and perceptual responses were assessed pre- and post-intervention. Following the laboratory experimentation a basic re-evaluation was conducted at the plant to assess whether the proposed changes had a positive effect on working postures, physiological and perceptual responses.

The results of the preliminary field investigation revealed a prevalence of awkward working postures and excessive manual work in both areas. Laboratory experimentation revealed a notable reduction in task demands pre- versus post-intervention. The PTT mean lean angle for two-handed pre-intervention pulling observations of 23.7° (±3.51) was reduced to 13.9° (±2.21) post-intervention. Low back disorder (LBD) risk was reduced during the two-handed pull intervention (from 36.8% ±8.03 to 21.7% ±5.31). A significant decrement in heart rate responses from 103 $bt.min^{-1}$ (±11.62) to 93 $bt.min^{-1}$ (±11.77) was recorded during the two-handed symmetrical pushing intervention. The electromyography (EMG) responses for one-handed pushing and pulling pre-intervention showed the highest levels of muscular activity in the right *medial deltoid* due to an awkward and asymmetrical posture.

CDC responses demonstrated that minor changes in the storage height of the door resulted in a significant reduction in sagittal flexion from 28.0° (±4.78) to 20.7° (±5.65). Predictions of average probability of LBD risk were significantly reduced from 50.3% (±5.91) to 39.8% (±5.10) for post-intervention car door lifting. In addition, the greatest reduction in EMG activity as a %MVC was achieved during sub-task ii (reduced from 35.1 to 13.7% and 30.5 to 13.9% for left and right *erector spinae* respectively) which was associated with the introduction of the transfer trolley for the door transfer phase of the CDC.

Re-evaluation in the automotive plant revealed that the most notable change has been the implementation of automated ride on trolleys in the Paintshop. The Bodyshop area has also been modified to allow more effective job rotation and the step into the storage bin has been reduced via a "low-cost" stepping platform. Mean heart rate recordings were reduced from 94 (±9.77) $bt.min^{-1}$ to 81 (±3.72) $bt.min^{-1}$ in the Paintshop. Overall the results demonstrate the effect of "low-cost" interventions in reducing the physical stresses placed on workers in the automotive industry where much of the work is still done manually.

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CHAPTER ONE
INTRODUCTION

BACKGROUND TO THE STUDY

Ergonomics, as an applied science, has a significant role to play in improving working conditions and productivity in Industrially Developing Countries (IDCs). Scott (1993) stated that each developing country has its own unique infrastructure and social circumstances, together with a specific labour force which merits specific research, detailed assessment and subsequent ergonomic intervention. It has been argued that people living in IDCs account for approximately 75% of the world's working population, and as O'Neill (2000) pointed out, the majority of these people still gain their livelihoods from rural pursuits, despite the increasing trend of urban migration. There is a large rural population within South African industry, with a significant number of semi-skilled people working in production areas where a mix of manual labour and highly advanced technology is evident.

Ergonomists practising in IDCs frequently identify sub-optimal working environments that place the operator at high risk (Shahnavaz, 1987; Kogi **et al.**, 1998; Scott, 2001; Renz and Scott, 2004; Scott and Christie, 2004). There is a need for input from trained personnel in improving many IDC working environments where poor work practice and low productivity are commonplace. Although the focus is on the work situation, the many extraneous problems associated with IDCs, such as poverty, chronic ill-health, increased physical and mental stress, leading to high absenteeism and turnover, all contribute to an increased likelihood of accidents and occupational diseases (Shahnavaz, 1987; O'Neill, 2000; Scott, 2001). The consequences of menial living and poor working conditions, and the resultant poor productivity are far reaching. The economies of many IDCs are underdeveloped, resulting in a "cumulative negative spiral" (Scott, 2001). It has been argued by Scott **et al.** (2003) that one of the best ways to reverse the spiral is to provide ergonomics input at relevant levels and ensure that the role of the human operator is considered when evaluating working areas.

Manual Materials Handling (MMH) tasks continue to predominate in IDCs (Charteris and Scott, 2001) and universally these have long been recognised as a major contributor to the occurrence of health complaints (Chaffin, 1987; Mital **et al.**, 1997; Marras, 2000). Heavy physical demands place the human operator under undue physical stress and increase the likelihood of the onset of work-related musculoskeletal disorders (WMSDs). This in turn results in an increase in suffering of the operator, and cost to the company concerned. There exists an urgent need to investigate the incompatibility between the human operator and the physically demanding tasks so many workers in developing areas are required to do. The focus of the present project was specifically on manual activities of operators in the automotive industry.

The South African automotive industry currently employs approximately 37 800 people in seven major manufacturing plants across the country (National Association of Automobile Manufacturers of South Africa (NAAMSA, 2006). The industry has experienced tremendous growth as a result of foreign investment and the opening up of new export markets post-1994. NAAMSA (2006) reported that capital expenditure (CAPEX) for this sector increased from R1.50 billion in 2000 to a projected R8.41 billion in 2006. International investment has facilitated the rapid development of automotive plants with various assembly lines being completely restructured. Export output has also increased significantly since 1995. According to figures released by NAAMSA (2006), total passenger car exports have risen from 8 976 (1995) to 195 400 units (2006). It is projected that this value will continue to rise to 200 000 units by 2007. This sector has potential for further growth through the Motor Industry Development Plan (MIDP), which was launched in September 1995 and was aimed at the development of an internationally competitive automotive industry (Department of Trade and Industry, 2002). The MIDP has proved to be highly successful and will subsequently be extended to 2012 (NAAMSA, 2006).

Despite the increased monetary investment little evidence is available within these industries to suggest that assembly areas of these new plants have been designed and constructed with much thought of the “human factor”. Numerous work-related hazards are clearly identifiable when walkthrough surveys are conducted by ergonomists. These surveys are a useful way of identifying risk in the workplace, and have particular value in IDCs where working conditions are often sub-optimal, as they identify the incompatibility evidenced between operator capabilities and excessive task demands imposed within the industry. Regretfully, ergonomics interventions in South Africa tend to be reactive rather than proactive and this trend is nowhere more apparent than in the automotive industry. Scott (1998) argued that ergonomists working in IDCs need to create an awareness of the theoretical principles, practical applications and benefits of ergonomics, in order to establish an “*ergonomics ethos*” and thus ensure that accepted principles are put into practice within industry. Ergonomics facilitation teams need to be formalised within these industries and sound principles adhered to in the design and application of interventions.

Although the South African automotive industry has focused on driver ergonomics in the design of vehicle units, it has placed little emphasis on adherence to sound ergonomics principles in the planning and implementation of the manufacturing and assembly processes. The operators working on assembly lines are thus frequently required to work in sub-optimal conditions, thereby increasing the likelihood of injury and reduced work efficiency. Hägg **et al.** (1997), reporting on the situation in well established areas, have identified that poor working postures and extensive MMH are prevalent in the automotive assembly line process; this is supported by Carey and Gallwey (1998), who commented that many assembly line tasks force the operator to adopt poor gross body postures, and to maintain these for the duration of the task. These excessive physical stresses, which are placed on the worker operating under these conditions, are universally recognised as being a major contributor to WMSDs (Häkkänen **et al.**, 1997). Pulling and pushing, carrying, lifting and lowering tasks are all evidenced in the automotive industry and usually involve working with awkwardly shaped objects such as doors, dashboards and even complete vehicle frameworks, which require manipulation at the extremes of joint range of motion (ROM).

The ratio of task demands to worker capacity has been shown to influence the occurrence of potential undesirable outcomes such as fatigue, discomfort and injury (Ayoub and Mital, 1989; Mital **et al.**, 1997; Dempsey, 1998; Marras, 2000). Tasks involving repetitive motions, high force application and vibration are common within the South African automotive industry (James, 2002a; James and Todd, 2003; James and Scott, 2006). The present study aimed to simulate high risk tasks identified in an automotive industrial setting within a controlled laboratory environment in order to conduct in-depth analyses of the tasks. Interventions were then developed aimed at minimising the risk to the worker *in situ*. The assessment of the viability of proposed interventions within the automotive plants was conducted. Where possible "low-cost" interventions were subsequently implemented in selected assembly areas with the prime objective being to reduce the physical demands placed on the worker and to improve worker efficiency. Furthermore, this study aimed to facilitate the evaluation of interventions through follow-up work conducted within the selected industry.

Scott (2001) argued that all role players should be encouraged to become involved, not only in identifying problem areas, but also in discussions of possible solutions. All problem areas and possible solutions were discussed with managers and workers, who were encouraged to provide feedback on the proposed changes, and a participatory process was established. This process arose out of the critical need to establish formalised ergonomics teams within the South African automotive industry, as identified by James (2002b). Members of the "Ergonomics Facilitation Team" established at GM included management, Safety, Health and Environment (SHE) officials and representatives of the workforce from selected areas of the assembly plant. The Facilitation team was subsequently invited to attend ergonomics awareness sessions conducted at the plant and provided with relevant materials and information.

STATEMENT OF THE PROBLEM

As the automotive sector is one of the leading manufacturing sectors in South Africa there is a crucial need to consider the role of the human operator in the manufacture of the vehicle unit, particularly with regards to the Paintshop and Bodyshop Closure Line areas. These process lines still require a high proportion of manual labour and the working postures adopted to execute the required manual tasks increase the likelihood of the onset of WMSDs. There is a clear need to identify major problem areas and for effective intervention strategies aimed at improving worker efficiency and safety, together with an increase in productivity within the automotive sector.

Two isolated work tasks were selected for laboratory investigation based on field observations. The automotive Paintshop work process involves the pushing and pulling of vehicle units on a “skid” transfer trolley platform during the working shift. The problems associated with these extreme loads (in excess of 600kg for some models) differentially tax the musculoskeletal system of the operator making this an essential area for further investigation. The Bodyshop areas require the handling of awkward vehicle panels, for example the front and rear doors, at the extreme limits of the workers’ ROM. The basic work-cycle required places substantial stress on the musculoskeletal system of the workers and warrants biomechanical analyses of working posture and force output requirements. The two independent tasks selected will be dealt with separately throughout the present study in considering the assessment of current work demands.

As limited research appears to have been carried out in the automotive industry, particularly in South Africa, it was deemed essential to conduct a holistic analysis of worker responses to physically demanding tasks in both the Paintshop (Task 1) and Bodyshop (Task 2) areas, and within a more rigorously controlled laboratory simulation of selected tasks.

RESEARCH HYPOTHESIS

The general research hypothesis is the same for both automotive tasks simulated under laboratory conditions to assess the Human responses pre- and post-intervention. It is hypothesised that the redesign of each of the two independent tasks in the laboratory will reduce the demands placed on the individual completing the specific task under investigation and decrease the biomechanical, physiological and perceptual responses of the worker. Responses collected during the pushing and pulling simulations of the Paintshop Trolley Transfer (PTT, Task 1) using the industrial Lumbar Motion Monitor (iLMM) are expected to demonstrate that kinematic stresses are considerably reduced post-intervention. Similarly, the Car Door Carriage (CDC, Task 2) simulation responses are expected to show that redesign has appreciably altered task demands by reducing the required ROM, twisting velocity and lateral velocities during task completion.

Physiological demands are also expected to decrease post-intervention for each of the two tasks, with changes being evidenced in heart rate and electromyography (EMG) responses. Working heart rates are expected to be notably lower following changes to the simulated worksite, thereby suggesting an overall decrease in predicted energy expenditure (EE) in the laboratory.

Modifications to the two separate tasks in the laboratory simulations are also expected to alter the participants' perceptions of the job, evidenced through changing Ratings of Perceived Exertion (RPE) and Body Discomfort (BD) ratings. Participants are expected to rate perceived exertion significantly lower following alterations to the worksite. Body discomfort is also expected to show decrements post-intervention, with participants rating fewer areas, and the level of discomfort reduced when compared with the current task demands.

STATISTICAL HYPOTHESES

The mathematical hypotheses for both the PTT (Task 1) and CDC (Task 2) are stated as the Null (H_o) and Alternative (H_a) hypotheses for laboratory simulation Human responses pre- and post-intervention. These hypotheses were framed as follows:

1.) Spinal kinematic responses are equal pre- and post-intervention

H_o: μ ROM; TV; LV $_{(Pre)}$ = μ ROM; TV; LV $_{(Post)}$

H_a: μ ROM; TV; LV $_{(Pre)}$ ≠ μ ROM; TV; LV $_{(Post)}$

Where:	ROM	=	Range of Motion (°)
	TV	=	Twisting Velocity ($°.s^{-1}$)
	LV	=	Lateral Velocity ($°.s^{-1}$)

2.) Physiological responses are equal pre- and post-intervention

H_o: μ HR; EMG $_{(Pre)}$ = μ HR; EMG $_{(Post)}$

H_a: μ HR; EMG $_{(Pre)}$ ≠ μ HR; EMG $_{(Post)}$

Where:	HR	=	Heart Rate Responses
	EMG	=	Electromyographic Activity

3.) Psychophysical responses are the same pre- and post-intervention

H_o: μ RPE; BD $_{(Pre)}$ = μ RPE; BD $_{(Post)}$

H_a: μ RPE; BD $_{(Pre)}$ ≠ μ RPE; BD $_{(Post)}$

Where:	RPE	=	Rating of Perceived Exertion
	BD	=	Body Discomfort Rating

DELIMITATIONS

The present study was delimited to the assessment of two distinct industrial tasks that were independently evaluated in the field and then separately simulated under laboratory conditions. The laboratory simulation of the PTT (Task 1) was divided into six sub-tasks, while the CDC (Task 2) was broken up into three sub-tasks.

The field sample consisted of Paintshop and Bodyshop workers with varied levels of practical work experience, with a range of one to 15 years. The field investigation was delimited to the responses of 12 male workers from the GM Struandale Plant, aged between 22 and 51 years. Field workers had no history of musculoskeletal disorders and were free from any serious injury (by self report) at the time of the study.

The participants in the laboratory experimentation were volunteer adult males. The study was delimited to the responses of 30 male subjects from Rhodes University, aged between 18 and 23 years. None of the participants had previous experience working in an automotive industry or completing MMH tasks. Laboratory participants had no history of musculoskeletal disorders and were free from injury (by self report) at the time of participation in the study.

The experimental procedures were confined to a laboratory environment. The influence of environmental factors such as temperature extremes (which could play a significant role when considering South African working conditions) were thus minimised by a light and heat controlled environment.

The holistic analysis of Human responses was conducted as part of both the field and laboratory investigations of the present study. Physical, psychophysical and organisational aspects were considered in assessing current workplace demands. Physical parameters evaluated included Human responses to biomechanical and physiological stresses. Psychophysical responses were also evaluated based on the perceptual ratings of both the workers and laboratory participants. Organisational analysis specifically focused on the industrial context where logistical changes to the workplace and work methods were carefully evaluated.

LIMITATIONS

The automotive worker and laboratory samples used in the present study were samples of convenience. The laboratory sample selected was not necessarily representative of the South African workforce. These factors therefore limited the reliability and reproducibility of the results to other populations other than the laboratory sample investigated, especially the automotive industry workforce.

Participants completing the laboratory simulations had no previous experience in completing manual tasks within the automotive industry. No work hardening or training programmes were completed prior to laboratory testing, therefore the present level of training could have influenced the responses to the manual work required in the laboratory sessions.

Psychological factors are known to influence the performance of test subjects. The motivation of test subjects was a factor which could have affected the results obtained for the MMH task assessments both *in situ* and in the laboratory sessions. No extrinsic rewards were offered, although comprehensive feedback was given to all subjects where possible.

Clinical history is a further significant factor in terms of both the field workers and student cohort particularly in the laboratory experimentation, although every attempt was made to ensure that the subjects were free from injury. There is a possibility that subjects could have been experiencing, but not reporting, some muscle strain before the testing commenced. This factor was beyond the control of the researcher in the present study.

Despite the period of habituation and the familiarisation trials given to each participant, it is possible that some subjects were still not comfortable with the equipment and procedures when recorded test bouts were completed. However, the potential impact of this limitation was minimised during the laboratory familiarisation where participants were shown video footage of the two independent industrial tasks and allowed to practice each of the simulations according to the techniques observed.

CHAPTER TWO
REVIEW OF LITERATURE

INTRODUCTION

The South African automotive industry still exhibits a prevalence of manual labour despite an increase in the levels of plant automation in this sector. The work-related demands placed on the human operator as a result of manual tasks are frequently excessive. Mital **et al.** (1997) stated that the ability of individuals to perform manual activities is frequently exceeded, resulting in chronic or acute injuries. The sub-optimal working conditions so typical of many industries in developing countries generally, and specifically the automotive industry, contribute to the onset of physical fatigue, which in turn will influence the physical and cognitive ability of the workers, ultimately resulting in below par performance efficiency. Kumar (2001) argued that humans are neither anatomically adapted to withstand the physical stresses nor are they mentally suited to endure the psychological stresses of the modern working environment. Operators are subjected to increasing mental and physical workloads in the automotive sector. The mental workloads have shown a dramatic increase with the greater utilisation of advanced technology.

The advances in manufacturing processes are evident when ergonomics surveys are conducted in various manufacturing environments (James, 2002a; Dempsey and Mathiassen, 2006). However, despite increased capital investment reported by the National Association of Automobile Manufacturers of South Africa (NAAMSA) between 1995 and 2006, little evidence is available within automotive industries to suggest that development of new assembly lines has been done with Ergonomics input or guidance. Dempsey (1998) argued that although automation and other technologies have reduced the need for manual labour in some working situations, particularly advanced industrial settings, there is still generally a widespread need for the manual handling of objects somewhere on the production or manufacturing line. Consequently, numerous hazardous situations are clearly identifiable when evaluations are completed by ergonomists. These workplace evaluations are a useful way of identifying problem areas in the workplace and have particular value in IDCs where working conditions are often sub-optimal (Shahnavaz, 1996; Scott and Shahnavaz, 1997), as they identify the incompatibility between operator capabilities and excessive task demands imposed within the industry. Regardless of the undeniable increase in cognitive requirements, the physical workloads relating to manual labour remain the major focus of this research.

Manual Materials Handling (MMH) tasks place physical stresses on the human operator that are manifested as strains on the musculoskeletal and cardiovascular systems (Dempsey, 1998; Kumar, 2001; James and Todd, 2003; James, 2005). It would appear that risk identification of workplace hazards relating to MMH, poor working postures and vibration has been largely neglected in the South African automotive industry. Various companies have attempted to establish basic health and safety teams that complete the role of assessing basic risks in the workplace; however, there remains a need to establish experts with a sound understanding of ergonomics principles to deal with task analyses and risk identification. It is important that all MMH tasks occurring in the production system are considered, not only those representing "hazardous" loads (Dempsey and Mathiassen, 2006). This is particularly relevant to the South African automotive industry where MMH tasks are widespread and the reporting of work-related musculoskeletal disorders (WMSDs) prevalent. Kumar (2001) stated that all risk factors for musculoskeletal injury can be placed in one or more of the following categories: genetic, morphological, biomechanical, physiological and psychological. The genetic and morphological characteristics are unique to each operator and cannot be altered. However, equipping key personnel with the required level of training to identify potential biomechanical and physiological risk factors should be given priority in the automotive industry. Early identification of high risk areas on the assembly lines will assist in minimising the incompatibility between the worker capabilities and the job requirements (Shoaf **et al.**, 2000), and will assist in the reduction of injury and WMSDs.

ERGONOMICS IN INDUSTRIALLY DEVELOPING COUNTRIES (IDCs)

IDC industries continue to experience the need for practical application of ergonomics (Shahnavaz, 1996; Scott and Christie, 2004; James and Scott, 2006; Scott and Renz, 2006). Working conditions are sub-optimal to poor in many instances and frequently result in high levels of absenteeism and injury in the IDC workplace. Scott (1998) stated that ergonomists working in IDCs need to create an awareness of the applications and benefits of ergonomics, and to ensure that accepted principles are put into practice within industry. Ergonomists working in IDCs such as South Africa are faced with a number of challenges in attempting to implement interventions based on sound ergonomics principles which will decrease the task demands placed on the human operator. Urlings **et al.** (1990) put forward the following possible reasons for the lack of implementation of interventions: attitudes of employees towards intervention strategies, resistance to change by managers and a lack of skills to apply changes. Although developing industries do provide ergonomists with substantial challenges, the long-term benefits have been shown to be far reaching with the benefits outweighing the costs (Hendrick, 1996; Scott **et al.**, 2003).

Although there has been a significant increase in the interest in, and commitment to, ergonomics in IDCs, managers frequently have so many problems to deal with that they perceive that they cannot afford the time nor the money for ergonomics (Scott **et al.**, 2003). The need therefore exists to focus on low cost or "no-cost" interventions in IDCs. Scott **et al.** (2003) proposed that initial ergonomics input in an IDC must be at a micro-level and must be of immediate effect in the workplace. In contrast to Industrially Advanced Countries (IACs), where the benefits of ergonomics have been well documented, intervention strategies in IDCs need to focus on reducing excessive physical and cognitive loads, while at the same time taking into consideration extreme environmental conditions, particularly in South Africa.

Important Considerations Relevant to Industries in IDCs

Physical Work Loads

The economies of most IDCs are not strong and many of the labourers are under-nourished, not physically robust and often in a poor state of health (Scott, 1999; Scott **et al.**, 2003). Despite these concerns, industries in IDCs continue to rely on heavy manual labour and furthermore, the labour force may often be regarded as expendable (O'Neill, 2000). Many operators are forced to work under sub-optimal conditions and the load factor is often neglected when task analyses are conducted *in situ*. Lifting of heavy loads is still commonplace, particularly in the automotive industry, and this augments the likelihood of WMSDs.

Shahnavaz (1987) argued that the outcome of heavy lifts, static work and harmful MMH is an increased incidence of accidents and a decrease in productivity. IDC industries typically exhibit a number of these indicators of sub-optimal working conditions and poor work design, and Dempsey (1998) stated that the ratio of task demands to worker capacity influences the occurrence of potential undesirable outcomes such as fatigue, discomfort and injury.

Cognitive Loads

Many of the stresses related to the completion of manufacturing tasks are now being attributed to the increase in cognitive workloads associated with increased task complexity. Shoaf **et al.** (2000) argued that the concept of a work hazard has been expanded to include non-physical hazards, specifically psychosocial, work organisation, disordered logistics and mental demands. Investment in new vehicle models and more automated assembly lines has brought about substantial change in the South African context and the cognitive demands placed on the operator have increased due to the use of more advanced technology. Dempsey and Mathiassen (2006) argued that ergonomics faces the challenge of developing work assessment tools that allow production stakeholders to integrate ergonomics into the continuous redesign of production, support and supply chains. Ergonomists conducting work in refurbished plants need to be aware of the changing focus of operations and ensure that the workers are sufficiently educated and trained to complete the redesigned tasks. Scott **et al.** (2003) stated that due to the dynamic nature of any work site, changes and inconsistencies will occur. In many instances the lack of conformity in work performance results from a lack of basic understanding of task requirements and a disregard of operator capabilities in redesign of the automotive work cycle. Shahnavaz (1996) emphasised the importance of providing appropriate education and training programmes that consider the specific conditions of IDCs and are adjusted to their needs and resources. The increased cognitive demands placed on the operator must be considered in general task evaluations, as this will have a substantial impact on the task-operator interaction.

Environmental Conditions

The South African automotive sector is affected by the general environmental conditions, which in turn will affect the work environment. High temperatures, excessive noise, poor lighting, vibration and air pollution are some of the key concerns. Heat stress is known to cause discomfort, a feeling of fatigue which leads to reduced work-rate, increased accident rates, carelessness and increased irritability (Ayoub and Mital, 1989). A study by Snook and Ciriello (1974) demonstrated that lifting, pushing and carrying ability declined significantly when temperature increased from 17.2 to 27°C. These figures are of particular relevance in the South African context where environmental extremes are frequently experienced. It was not uncommon to record temperatures in excess of 27°C in the IDC automotive industries assessed in the present study, and high temperatures in the Bodyshop and Paintshop are of prime concern due to the physical nature of the tasks completed in these areas of the automotive plants.

THE AUTOMOTIVE INDUSTRY IN SOUTH AFRICA

Growth and Development in the South African Automotive Sector

The automotive industry in South Africa is highly organised and has experienced major growth as a result of foreign investment and enhanced access to financially lucrative export markets. Employment and production capacity have grown over the past five years with potential for further rapid expansion (National Association of Automobile Manufacturers of South Africa (NAAMSA, 2006). Global partnerships have facilitated the reconstruction of many automotive plants with various assembly lines being completely revamped. Over the last eight years export output has risen substantially (NAAMSA, 2006).

The Motor Industry Development Programme (MIDP) was developed with a number of key objectives in mind, including: the provision of high quality and affordable vehicles and components to the domestic and international market, the provision of sustainable employment through increased production, and the economic growth of the country by increasing production and achieving an improved trade balance. Increased volumes and higher levels of employment have already seen many of these objectives reached in this sector. A recent decision was taken to extend the MIDP until 2012 (NAAMSA, 2002). The automotive industry is widely regarded as a South African success story in the development of international supply networks.

Ergonomics in the South African Automotive Industry: The Current Situation

Assessments of the current level of knowledge of ergonomics within the South African automotive industry identified a limited understanding of the discipline amongst key role players (James, 2002b). A growing number of industries conduct basic walkthrough surveys, but follow-up investigations are limited. Insufficient time and resources are spent on implementing intervention strategies aimed at improving the working environment for the human operator. Personnel are frequently inadequately equipped to identify high risk tasks and do not have the required level of training to ensure that changes are adopted.

A survey of current employee perceptions towards ergonomics was conducted in four independent automotive plants in South Africa (James, 2002b). Respondents were randomly selected from diverse areas of these industries, including employees from the "shop-floor" to those at a senior managerial level. This survey aimed to compare the present ergonomics initiatives to established safety standards utilised by these plants. Key findings revealed the following: in contrast to safety, ergonomics facilitation teams were not established within these automotive plants; respondents all rated current ergonomics initiatives as average to poor; and personnel highlighted the need to formalise "Ergonomics Facilitation Teams" thereby encompassing greater managerial involvement. It should be noted that although respondents felt that automotive plants adequately dealt with safety issues, they did perceive the need for a greater emphasis to be placed on regulations and the adherence to basic industry standards with regards to working practice (James, 2002b).

Automotive plants in South Africa are a challenging mix of "state-of-the-art" technology in some areas and a predominance of MMH in the older areas of the plant (James and Todd, 2003). Many areas of the automotive assembly process are in dire need of design inputs based on sound ergonomics principles. James and Scott (2006) reported that minor workplace design changes and interventions have frequently been proposed within the automotive sector, but many manual work problems still remain. There is still clearly a need to focus on risk identification and to facilitate the development of ergonomics teams within these plants. The South African automotive industry highlights a specific need for ensuring that participation is encouraged from the workforce to allow operators to understand the reasons for changes in working methods before the implementation process commences.

MANUAL MATERIALS HANDLING (MMH)

MMH tasks are varied in nature and include lifting, lowering, pushing, pulling, carrying, loading and unloading of objects in an industrial setting (Snook **et al.**, 1970; Mital **et al.**, 1997; Bridger, 2003; Dempsey, 2003). Many of the objects moved are of an awkward size and shape, and therefore necessitate the worker to adopt poor gross body posture. Excessive physical demands are placed on the human operator under these conditions and are frequently shown to be a major contributor to WMSDs (Häkkänen **et al.**, 1997; Ferguson and Marras, 1997; Marras **et al.**, 2006). Dempsey (1998) stated that MMH tasks are present in many service and manufacturing industries, and are a significant source of compensable injuries. There are a number of concerns relating to heavy manual work as the mass of the load being lifted is transferred to the spinal column in the form of compression, shear and torsional forces (Mital **et al.**, 1997; Marras **et al.**, 2003). The prevalence of low back disorders (LBD) and work-related upper limb disorders (WRULDs) thus demand a more detailed focus in the present study.

Types of Activities Observed in the South African Automotive Industry

Despite mechanisation and automation, manual work continues to be common in industrial settings, particularly in developing areas (Kumar, 1995; Dempsey, 1998; Scott **et al.**, 2003). Dempsey (2003) stated that MMH continues to represent a major loss source in the workplace, resulting in a need for research and practice to address the design and evaluation of MMH exposures. The automotive manufacturing process requires the completion of a number of specific manual tasks. James and Todd (2003) observed that operators frequently adopt sub-optimal working postures during the completion of tasks along the automotive assembly line process. Lifting, carrying and lowering of vehicle panels are probably the most commonly used manual activities in the Bodyshop environment. Engine assembly lines require the operator to lift, carry and place heavy engine components, including crankshafts, without mechanical assistance. The Paintshop areas require frequent skid or trolley pushing and pulling, which taxes the operators working in this particular area of the manufacturing process. The trim and assembly line also place a significant amount of strain on the worker as many of the tasks are repetitive in nature and require awkward postures to be adopted.

Lifting and Lowering

Lifting from industrial storage bins is frequently observed in the automotive Bodyshop and Trim Line assembly areas. Ferguson **et al.** (2002) stated that different lifting techniques may influence the risk of LBD. Asymmetrical lifting and associated postural changes therefore affect the biomechanical responses of the operator and could precipitate the onset of WMSDs. They further argue that guidelines for design of these containers and lifting styles have not been widely researched and require the attention of ergonomists working in this area. The storage of panels and parts is one area that requires further investigation when considering the automotive sector. Figure 1 illustrates how a Bodyshop operator is required to lift a vehicle panel from a storage bin using a free-style lifting technique and carry the panel to the welding “jig”.

Figure 1: *A Bodyshop operator is required to lift and carry a body panel from an industrial storage bin in a South African automotive industry.*

Work conducted by McKean and Potvin (2001) assessed the effects of a simulated industrial storage bin (similar to the container in Figure 1) on lifting and lowering posture and trunk extensor muscle activity. The findings of this study are of particular relevance to the automotive industry, as many of the Bodyshop and Trim Line tasks require a lift constrained by a physical barrier. In many cases the operator is required to stoop and stretch into the storage bin during the execution of the working cycle. McKean and Potvin (2001) concluded that there were a number of factors which suggest that poorly designed industrial storage bins could increase the risk of injury when lifting or lowering loads. These risk factors included an increase in peak trunk flexion, which resulted in the surface of the lumbar intervertebral discs (IVDs) becoming more vertical, thereby increasing the shear force acting on the IVDs with significantly greater electromyographic (EMG) activity being registered in the *erector spinae* during constrained lifting.

Dempsey (2003) evaluated findings associated with lifting and lowering tasks as part of an epidemiological study investigating the relationship between lower back workers' compensation claims and physical demands of lifting and lowering tasks. This research highlighted the importance of the load of the object being moved during lifting and lowering tasks. In addition, vertical range data showed that there are a number of lifting and lowering scenarios where lift and subsequent lowering takes place outside the desired vertical range for both the origin and destination of the MMH task. Of all the factors considered during the assessment of lifting and lowering, Dempsey (2003) argued that load emerges as perhaps the most important factor for consideration in the investigation of LBD causality.

Lifting and maneuvering of objects takes place from palletised storage bins in many automotive work settings. The location of the pallet and consequent origin of the lift has a significant effect on torso kinematics during lifting tasks (Jorgenson **et al.**, 2004). Researchers have sought to provide guidelines on safe pallet location, and NIOSH (1991) suggested that the pallet should be orientated in a 90° position to the lifting origin. Findings from research completed by Jorgenson **et al.** (2004) demonstrated a notable increase in biomechanical loading when participants were required to step and reach a simulated load. The Bodyshop areas require a similar step and reach during the lifting of car door panels and subsequent increases in spinal loading were therefore expected. Although the pallet orientation was found to be an important consideration, Jorgenson **et al.** (2004) argued that keeping the load closer to the workers' lift origin would appear to be more important than ensuring a 90° pallet orientation. This is an important consideration in the evaluation of sub-optimal lifting or lowering task layouts as is commonly observed in the South African automotive industry.

Carrying

Load carriage is commonplace among humans in all walks of life (Scott and Ramabhai, 2000). In the manufacturing sector load carriage may require the operator to lift and carry a part of a high mass over a considerable distance. Observations in the South African automotive industry demonstrated that current task demands are frequently excessive and working postures particularly poor during load carriage (James and Scott, 2006). Bridger (2003) stated that carrying increased the load on the body in two ways. Firstly, the increased load results in an increase in the physiological cost of walking by elevating the overall load placed on the muscles of the legs. Secondly, the method by which the load is held, or attached to the body, can be an additional source of postural stress. The carriage of vehicle panels and parts is frequently seen in the South African automotive assembly environment. Operators are required to physically manipulate awkwardly shaped panels and parts, thereby placing excessive strain on the musculoskeletal system. Kroemer and Grandjean (1997) argued that handling loads often involves a good deal of static and dynamic effort, enough to be classified as "heavy work".

Figure 2 highlights the posture adopted by the human operator while carrying a car door on the Bodyshop Closure Line of a South African automotive industry. It is therefore not only appropriate for the Ergonomist to consider the load of the vehicle panel, but also the size and shape of the panel moved during load carriage. Research has suggested that loads should be positioned as close to the body as possible in order to minimise energy expenditure (EE) while carrying (Mital **et al.**, 1997; Bridger, 2003). If an object is carried further away from the body static contraction will result in order to stabilise the worker during the completion of the normal gait pattern. The result during sustained carrying will be local muscle discomfort and fatigue due to the worker adopting an inappropriate carrying technique (Bridger, 2003).

Figure 2: *A Bodyshop operator manually lifts a car door on the closure line.*

Scott and Walraven (1990) reported that while the literature is replete with research done on manual work in vast areas of developed countries, very little appears to have been reported on the South African situation, and it is evident that limited work has been carried out aimed at assessing the impact of task demands on worker efficiency in the automotive sector. Operators are frequently required to complete highly demanding tasks increasing the risk of personal injury. Selected tasks observed in the automotive sector, for example the door carry, therefore necessitate additional research in determining the likelihood of injury or increased reporting of muscular discomfort. The door carriage task is one of the more physically demanding due to the load, size and shape of the part being moved and was thus focused upon in the present study.

Pushing and Pulling

The indisputable evidence in the literature that lifting and carrying are major sources of work-related injury has led to a much greater use of manual handling devices (MHD) more recently (Haslam **et al.**, 2002). The frequency of pushing and pulling tasks has therefore increased, and Baril-Gingras and Lortie (1995) have argued that manual work activities frequently require the operator to exert repetitive, submaximal forces. The design of working areas and the nature of these push-pull tasks have resulted in Hoozemans **et al.** (1998) reporting that 9 - 20% of the injury claims for low back pain were associated with pushing and pulling activities. Earlier work carried out by Snook (1978) stated that the evaluation of the majority of pushing and pulling work is aimed primarily at the assessment of the initial forces exerted to accelerate the object, and the quantification of the sustained forces exerted to keep the object moving at approximately the same velocity during the completion of the push-pull task. Following the collection of field responses, maximum acceptable forces should be psychophysically determined to correspond to the actual work situation for pushing and pulling activities (Snook and Ciriello, 1991; Mital **et al.**, 1997).

It is universally acknowledged that many over-exertion injuries occur due to pushing and pulling in industry (Lee **et al.**, 1991; De Looze **et al.,** 2000; Todd, 2005). The execution of pushing and/or pulling tasks in the automotive industry requires the worker to move heavy and awkward vehicle frames on a frequent basis during the standard 8-hour working shift. The high forces required in many of these push and pull tasks necessitate the operators to take up working postures which result in the centre of mass (CM) being located at the extreme limits or even beyond their support base (BS), which in turn significantly increases the likelihood of slip, trip and fall (S,T and F) accidents (James and Todd, 2003). Figure 3 illustrates the posture adopted by an operator in the Paintshop of a South African automotive industry during task completion. The operator is clearly subjected to a high risk task in this occupational setting and is likely to injure himself as a result of either fatigue due to repetitive movements or a slip-trip accident (James and Todd, 2003; Todd **et al.**, 2004).

Figure 3: *The pulling of a vehicle frame on a trolley platform.*

Work conducted by James and Todd (2003) assessed the impact of pushing and pulling tasks on the human operator working in an IDC automotive industry. This study revealed that there were substantial differences in the maintenance of the roller systems on which the vehicles were being moved, thereby increasing the resistance of the support base and subsequent force output required on the part of the worker. Furthermore the operator was required to push and pull the vehicles over uneven surfaces, increasing the likelihood of tripping. Haslam **et al.** (2002) stated that slipping is more likely when pushing or pulling than with unencumbered gait owing to higher shear forces between feet and floor. Research conducted by Manning (1983) provided a number of possible causes for increased occurrence of S, T and F incidents, including: slipping off a step, rung or platform; a trip over a projecting rung or step; unintentional stepping off the underfoot surface and loss of balance from careless or rapid movement. These potential hazards are commonplace in the automotive industry. Furthermore, Laursen and Schibye (2002) argued that the type of surface significantly affected the magnitude of push and pull forces, both in the initial and sustained phases of the task.

The mass of the object being moved by pushing or pulling is an essential consideration for the ergonomist. The trolley platforms used in many South African Paintshops require the worker to move substantial loads of 190kg to 600kg under conditions that are frequently sub-optimal. In similar situations Hoozemans **et al.** (2004) report that the loading of the low back and the upper extremity have largely been the focus of research in this area. De Looze **et al.** (2000) proposed that pulling has been associated with a greater increase in the net moment at the low back than pushing. Compressive and shear forces as a result of push-pull tasks have also been widely researched (Lee **et al.**, 1991; Resnick and Chaffin, 1995; Lavender **et al.**, 1998), with the compressive forces acting on the low back during pulling generally being reported to be higher than those associated with pushing. Hoozemans **et al.** (2004) provided two possible explanations for greater compressive forces associated with pulling. Firstly, the net moments at the low back have been reported to be higher during the completion of a pulling task. Secondly, most studies erroneously utilise a simplified "single muscle model" where net moments are the result of activity of either one back or one abdominal muscle. Pulling would therefore result in higher compressive forces because the lever arm of the trunk flexors in these models is much larger than the lever arm of the trunk extensors (Andres and Chaffin, 1991; Lee **et al.**, 1991; Gagnon **et al.**, 1992).

Hoozemans **et al.** (2004) assessed the mechanical loading of the low back and shoulder while pushing and pulling loads ranging from 85 to 320kg. Initial exerted forces were found to be the highest measured during the laboratory tasks evaluated. The initial forces were also relatively highly correlated with the initial and maximum low back net moments. They found lower correlations between exerted forces and mechanical load at the low back and shoulder during the sustained pushing or pulling actions. This research provided two possible reasons for the lower levels of association between mechanical loading and sustained force measurement. Firstly, they argued that the direction of the force exerted with respect to the joints being used will play a significant role in mechanical loading and should be taken into account (De Looze **et al.**, 2000). Secondly, that posture and movement patterns largely determined the mechanical load compared to the exerted forces.

Hoozemans **et al.** (2004) cautioned that a number of task-related effects are present during pushing and pulling, and that forces exerted during either the initial or sustained phases should not be used as the critical indicator for mechanical loading. Consideration of the posture adopted, movement pattern, friction from the working surface and design of the trolley or cart are equally important in decreasing task demands (James and Todd, 2003; Hoozemans **et al.**, 2004).

Lee **et al.** (1991) contend that cart or hand-truck pushing and pulling are common dynamic tasks in industrial settings and the worker needs to ensure that control over the device is maintained to minimise the risk of accidental operation. However, dynamic pushing and pulling require different working postures and will differentially tax the musculoskeletal system (James and Todd, 2003). The handle height of the trolley or cart has been shown to be important, as a higher pushing or pulling point will result in a decrease in the net moment at the low back (Hoozemans **et al.** 2004). The ergonomist must therefore carefully assess the nature of task demands, and Lee **et al.** (1991) caution that static pushing or pulling research must not be inappropriately applied to dynamic pushing and pulling tasks. The push-pull tasks observed in the South African automotive industry were included in the present study. The nature of task completion and hazards to the operator were evaluated *in situ* and the relevant sub-tasks then simulated in the laboratory setting.

Todd (2005) reviewed the current trends in pushing and pulling research and he pointed out that although a great deal of research has focused on static pushing and pulling there is still a need to assess dynamic activities, particularly in IDCs. He argued that the application of findings based on static isometric efforts has limited applicability when considering freestyle cart or trolley pushing or pulling. A major area that has been identified for further research involves physiological responses to dynamic pushing and pulling. Todd (2005) therefore suggested that there is a need to focus on heart rate and EMG responses in order to derive applicable predictions of energy expenditure specific to dynamic activities.

Factors to Consider when Assessing MMH Tasks

Manual handling has been shown to be highly prevalent and instrumental in creating a number of complex problems for workers in IACs and IDCs (Dempsey, 1999; Scott and Christie, 2004). Engine assembly and Bodyshop areas of the automotive manufacturing process are of prime concern, as many tasks are completed under sub-optimal working conditions (James, 2002a; James and Todd, 2003; James and Scott, 2006). The key research in this area has focused largely upon the load, task frequency and work shift duration. In addition, vertical and horizontal measurements have been widely considered during the evaluation of MMH (Marras **et al.**, 1993; Davis and Marras, 2003; Dempsey, 2003).

Load

Load is of prime importance when evaluating any manual task in IDC industry. A load is generally characterised by its shape, size and mass (Mital **et al.**, 1997). Heavy and awkward objects are regularly lifted in a number of areas of automotive plants, particularly the Bodyshop, and are evidenced in the form of large vehicle panels or parts (James, 2002c; James and Scott, 2006). IDC industries frequently require operators to manually lift loads in excess of 50kg, thereby predisposing the operator to WMSDs. Work carried out by Snook (1978) demonstrated that an operator was three times more susceptible to low back injury when lifting loads that were not deemed to be acceptable to the industrial population. In an attempt to regulate loads lifted in industry, the National Institute for Occupational Safety and Health (NIOSH) developed a number of basic guidelines for manual work (NIOSH, 1981; Waters **et al.**, 1993). Waters **et al.** (1993) completed the revision of the NIOSH (1981) equations in response to criticism from various researchers and practitioners. Ciriello and Snook (1983) argued that the size of the object, distance carried, height and frequency are significant variables to consider when establishing guidelines for maximal acceptable lift (MAL).

Nicholson (1989) argued that load limits can broadly be defined under two general categories, namely "acceptable limits", derived from what a worker is willing to handle, and "safe limits", based on biomechanical and/or physiological criteria which are considered potentially dangerous to exceed. Genaidy **et al.** (1998) stated that one of the work practices most frequently taught to employees is to estimate the heaviness of the load before it is handled. The practical application of an acceptable-limit model in an IDC industry is a complex process, as the level of operator education is not always necessarily adequate to ensure a high level of understanding relevant to task criteria. Furthermore, actual classification of a "heavy" load has provided researchers with a number of questions. Genaidy **et al.** (1998) stated that limited information can be found in the Ergonomics literature about what a person perceives to be a heavy load. Results from work conducted by Marras **et al.** (1993) indicated that moment differences were driven by loads rather than moment arms. Furthermore, when comparing the work of Marras **et al.** (1993) and Waters **et al.** (1999), findings show that load remains the most important factor in the development of LBD due to increased spinal loading. Clearly increased load will play a significant role in both workplace fatigue and subsequent LBD in instances where lifting/lowering, carrying and pushing/pulling manual tasks predominate (Dempsey, 2003).

Davis and Marras (2003) assessed the relative contributions of biomechanics, psychosocial factors, and individual risk considerations in the development of spinal loading. Findings from this study demonstrated that load weight remains the major contributor to spinal compression, while individual characteristics accounted for the majority of anteroposterior shear variability (Davis and Marras, 2003). Perhaps most importantly this study demonstrated that the load placement is one of the largest influencing factors on resultant spinal loads. Load placement is a unique stressor, in that it has both biomechanical and psychosocial components (Davis and Marras, 2003).

Frequency

Frequency of handling is an important task characteristic which influences an operator's capability to perform MMH activities (Marras **et al.**, 2006). High frequency of task completion decreases the MMH capacity of the worker, particularly when considering the entire working shift, and Mital and Manivasagan (1983) concluded that task frequency had a significant effect on the maximum acceptable mass of the lift evaluated.

Increases in product demand within the South African automotive industry have resulted in higher working frequencies as assembly plants aim to meet higher production goals (NAAMSA, 2006). Increased task completion frequency has necessitated that the mass of the load moved be reduced to ensure that the operator is not excessively taxed during the working shift. Khalil **et al.** (1985) reported that for a given MMH task, the maximum load of lift acceptable to an individual decreases non-linearly with an increase in frequency. The ergonomist working in this sector therefore needs to carefully scrutinise the task requirements and ensure that the demands placed on the human operator are not excessive when the complete lifting situation is considered.

Previous studies have largely focused on lift frequency-related increases in heart rate, oxygen consumption and energy expenditure (Garg, 1989). The assessment of spinal loading provides a further method of evaluating the role of frequency in MMH. Marras **et al.** (2006) have shown in a recent study that the response of an individual to lift frequency will largely determine the work efficiency of the work cohort. The primary objective of this research was to determine how spinal loading changes in response to lifting frequency exposure, load lifted and the duration of the lifting task. The comparison of spinal responses of novice and experienced manual handlers also provides a useful base of comparison for the present study due the inexperience in manual labour of the laboratory sample. Findings from the Marras **et al.** (2006) research demonstrated a number of interesting findings with respect to the effects of lifting frequency and role participant experience on spinal loading. Marras **et al.** (2006)

found that experienced MMH workers had increased spinal loading at lower lifting frequencies, while novice lifters had higher loading at higher frequencies, and propose that increases in lifting frequency resulted in an increase in spinal loading due to higher levels of coactivity, particularly when participants are not experienced in MMH.

Duration

Scott (1999) stated that due to poor income and living conditions, many people working in IDCs may work arduously long hours, often more than eight hours per day. Together with the duration of the work shift, it is also necessary to consider the duration of the task which will affect the successful completion of the task, and Mital **et al.** (1997) argued that the duration of performance is an important consideration in designing an MMH job. An increase in task duration will increase the overall level of energy expenditure during the everyday work shift, and the metabolic energy expenditure level that can be maintained over time decreases with an increase in the task duration (Ayoub and Mital, 1989). The physical demands of a manual task should therefore be reduced as the task duration increases. A noteworthy difference between IACs and IDCs relates to the regulation and enforcement of legislation specific to an eight hour working shift. In IDCs it is not uncommon for members of the workforce to complete shift cycles in excess of 10 hours per day (Scott, 1999).

The duration of a working shift will have a notable influence on biomechanical, physiological and perceptual responses of the worker. Marras **et al.** (2006) evaluated biomechanical loading during an eight hour shift and found that compression in the spine was greatest during the first two hours of the work bout. There was also a 4% increase in compression at the end of the working shift. EMG analyses showed that higher spinal loads occurred later in the day due to increases in muscle coactivity.

Low Back Disorders (LBD)

Cumulative low back loads are receiving widespread attention as a method of identifying jobs and individuals who are at high risk of developing LBD in the workplace (Callaghan **et al.**, 2005). Physical loading on the lower back in the place of work, in particular high peak forces and poor trunk postures and movements, have been presented as contributors of the reporting of LBD in various industries (Marras **et al.**, 1993; Marras **et al.**, 1995; McGill, 1996; Norman **et al.**, 1998; Davis and Marras, 2003). Work conducted by Marras **et al.** (1999) suggested that LBD continue to be the most common musculoskeletal problem. These high levels of reporting of particular concern to ergonomists working in IDCs where manual work predominates. Many leading ergonomists are concerned that the problem associated with manual work related injuries will not be resolved easily, and the costs associated with these injuries continue to rise (Ferguson **et al.**, 1992; Dempsey, 1998; 1999; Davis and Marras, 2003).

McGill (2004) argued that research into factors relevant to LBD indicates that too little loading is detrimental to the individual as is too much loading. He points out that individuals who are predominantly sedentary and not required to load their spine or muscular system may in fact be equally at risk in the workplace with regards to LBD. In contrast, the experience of the workforce in physically demanding manual jobs is an important consideration when considering the likelihood of LBD. Recent work completed by Marras **et al.** (2006) aimed to determine how spine loading changes in response to lift frequency exposure, weight lifted and lift duration over an entire shift. Furthermore, this study aimed to assess whether differences exist between the responses of novice and experienced manual materials handlers. The results from this research demonstrated that experienced participants had on average 13% less compressive load on their spines compared to novices completing the same lifting tasks. Marras **et al.** (2006) further argued that it was not lifting frequency alone, but frequency and moment in combination that influences spinal compression. Of particular relevance to IDC industry is the finding that experienced workers are most likely to be used to lifting at greater frequencies and have optimised their muscle recruitment patterns so that they minimise cocontration and the subsequent loading (Marras **et al.**, 2006). Workers therefore need to be trained in appropriate lifting techniques and clearly advised on the most appropriate methods for sub-task completion.

A key challenge to researchers investigating LBD is deriving feasible guidelines or limits that have applicability in the workplace. McGill (2004) has suggested that advances in the prevention of occupationally related LBD will require further evidence justifying the various terms needed for a robust and valid biomechanical model. Automotive industry SHE officials frequently request guidelines for safe lifting limits and find the revised NIOSH model (Waters **et al.**, 1993) to be complex and limited in its workplace application (Visser, 2004; Khumalo, 2004). Future models aimed at assessing the risk specific to LBD should include terms for load magnitude and mode, repetition and duration, together with consideration of age and gender, previous tissue damage and the benefits of rest periods (McGill, 2004). In IDCs there appears to be a need for simplistic guidelines which are easily applied, and useful in proactive prevention of LBD. Another limitation of predictive models is individual differences in spinal responses (Campbell-Kyureghyan **et al.**, 2005). The spine is not a rigid body, but rather a multi-joint structure that will vary substantially in shape from person to person; she purports that the load distribution and resultant spinal motion will consequently vary substantially based on individual differences.

Ferguson **et al.** (2005) previously suggested that one of the best predictors of LBD is previous history. Many workers return to the workplace with very simple lifting guidelines and in the case of IDCs only nominal restrictions on what load may be lifted during the working shift. Additionally, while physical loading may be limited, working posture and origin of lift are not restricted (Ferguson **et al.**, 2005). Many individuals in the workplace therefore place themselves at great risk of re-injuring themselves due to the working posture they adopt. The point of origin of the lift is not strictly controlled and in many instances the lifting action requires an extreme horizontal reach, particularly in the case of palletised loads. Marras **et al.** (2004) concluded that spine loading is greater in participants with LBD compared to asymptomatic individuals when performing similar lifting tasks. Interestingly their study demonstrated that counterclockwise lifting yielded much greater spine loading than clockwise lifts. The authors contend that the differences in spine loading between groups with LBD and asymptomatic groups appears to be related to differences in muscle coactivation and possibly to perceived individual needs for system stability (Marras **et. al.**, 2004). In the case of inexperienced manual handlers, the EMG pattern is expected to differ substantially due to perceptions of task demands and perceived need for stability. McGill **et al.** (2003) stated that the amount of muscle activation needed to ensure sufficient stability depends on the task being completed, stating that for daily living activities very modest levels of abdominal wall coactivation is usually adequate to complete a simple, light weight lift. In contrast, workplace lifting tasks where loads in excess of 20kg are moved will frequently require higher levels of muscle coactivation to allow the individual to reach an acceptable level of stability. A basic understanding of muscle coactivation is useful during the assessment of manual handling tasks, but McGill (2004) cautioned that spine stability, or the strategy to ensure that the spine does not experience instability, depends solely on the motion and motor patterns chosen by the individual.

In addition to increased trunk muscle coactivation, fatigue failure of the lumbar spine will have a marked effect on the prevalence and reporting of LBD. Gallagher **et al.** (2006) suggested that the magnitude and distribution of loads on structural components of the lumbar spine vary considerably. Some of the key factors for consideration include the posture adopted, the size of vertebral bodies, the degree of disc degeneration, and the magnitude of the shear and compression forces imposed on the spine. Results from this study suggested that prediction of specific failure modes for older lumbar motion segments may be possible given the knowledge of the specimen size, disc degeneration status, degree of flexion and spine loading characteristics (Gallagher **et al.**, 2006). Findings from this research have important application in the workplace where older workers are required to complete physically taxing manual work and may be returning to work after an injury. Higher incidence of LBD is to be expected in instances where the workforce and the task demands are incompatible.

A major concern facing ergonomists working in the automotive industry relates to the current level of training and understanding of risk of LBD in this sector. Marras (2000) identified a key concern when stating that control of risk in the workplace requires knowledge beyond simple identification of key factors. It requires a much deeper understanding of how risk of LBD occurs at the workplace. While selected personnel may be equipped to identify high risk tasks, the need for input from an ergonomist in redesigning of a particular workstation to minimise risk should be given priority. In many IDCs the risk of LBD is misunderstood, underestimated and underreported. Dealing with the potential pitfalls of manual work will require a focused, long-term approach that goes beyond the "quick fix" and leads to substantially greater improvements in workplace conditions (Dempsey and Mathiassen, 2006).

Assessment of MMH Tasks

The use of manual labour is widespread in the automotive industry despite significant workplace changes and the increasing use of advanced technologies in the sector. Internationally, MMH has been the focus of extensive critical review and clinical studies aimed at establishing criteria to be used to assess and subsequently intervene in instances where manual handling poses major risks to the worker (Dempsey, 1998; Ciriello **et al.**, 1999; Marras, 2000; Davis and Marras, 2003).

These approaches can be sub-divided into four principle areas as follows: the role of epidemiology, the biomechanical, the physiological, and the psychophysical. In most instances suitable guidelines developed for MMH tasks cannot be formulated from a single factor, but require an integrated, holistic approach. Consequently it has been proposed that MMH models should be formulated on the basis of multiple criteria (Charteris **et al.**, 1976; Dempsey, 1999). There is a need for both basic and applied research to enhance the methodologies for aggregating multiple-component MMH tasks and MMH criteria (Dempsey, 1999).

The Epidemiological Approach

NIOSH (1981) defined epidemiology as a science which identifies the incidence, distribution and potential control of injury or illness related to a specific population. The basic emphasis of epidemiology is on groups of workers rather than on the individual operator (Mital **et al.**, 1997). Dempsey (1998) suggested that the role of epidemiology in the development of MMH criteria was threefold: determining/verifying the aetiological significance of a given variable; verifying the validity of a given criterion by establishing the relationship between a specific variable and the probability of injury or disability; and providing guidance in the development of a criterion through consideration of previously determined relationships between a given variable and selected outcome measures. However, the direct utility of epidemiological models has been questioned in a number of instances due to the high levels of specificity of this approach to the assessment of MMH activities (Mital **et al.**, 1997).

Ayoub **et al.** (1997) argued that a critical research need in the area of MMH is the epidemiological comparison and validation of criteria based on different approaches. Work conducted by Marras **et al.** (1995) aimed to merge existing epidemiological models with biomechanical mechanisms in assessing risk factors related to MMH task completion. In this research over 400 jobs across 48 industries were compared in order to measure *in situ* trunk kinetics and kinematics. The magnitude of trunk lateral velocity, twisting velocity and sagittal angle, as well as lifting frequency and load moment were positively related to jobs which were historically classified as low, medium or high risk for the development of low back pain (Marras **et al.**, 1995). While this research does have a number of limitations, it is widely regarded as a significant attempt to merge the epidemiological and biomechanical approaches in research and practical terms. One of the major obstacles facing ergonomists assessing manual work is that the epidemiological evidence supporting a link between risk factors and injury is either unavailable or the data support only a qualitative link (Mital **et al.**, 1997). Kuiper **et al.** (1999) argued that in spite of the common belief that MMH activities are associated with the high incidence of industrial injuries, particularly to the lower back region, conclusive evidence has still eluded ergonomists. It is therefore critical that the epidemiological models developed be carefully scrutinised and not looked at in isolation when assessing manual tasks.

The Biomechanical Approach

The biomechanical approach aims to ensure that tasks are designed in such a way as not to exceed the capacity of the musculoskeletal system (Dempsey, 1998). Various approaches have been utilised to assess the biomechanical demands placed on the human operator. Andersson (1985) has argued that two biomechanical-based approaches have been widely used to establish safe practices for manual work. The first approach has been to assess the interaction between the operator and the task. The researcher is thereby able to determine whether the physical characteristics of the worker are morphologically suited to safely endure the physical demands of the task. A number of rating scales and safe practices guidelines have been developed using this paradigm. Chaffin **et al.** (1978) developed the job strength rating (JSR), while Ayoub **et al.** (1978) developed basic guidelines based on the job severity index (JSI).

The second approach is to make use of compression limits and maximal joint torques, which are reportedly the most commonly used for biomechanical assessments of MMH tasks (Dempsey, 1998). There are a number of force-related biomechanical models which have been developed to assess the response of the musculoskeletal system to mechanical stresses (Ayoub and Mital, 1989). The biomechanical model essentially requires the human musculoskeletal system to be treated as a system of links and joints (Mital **et al.**, 1997). Differences in approach to this particular paradigm have been largely related to the classification of the number of links assessed and the technique used for analysis. Mital **et al.** (1997) argued that two or three dimensional techniques could be used to assess the mechanical stresses the human body is subjected to during completion of MMH tasks. One of the principle concerns with regards the use of compression and force-related biomechanical methods relates to the deficiencies in data utilised to formulate these criteria. Compression limits have largely been formulated based on cadaver responses. Dempsey (1998) questioned whether the *in vivo* spine responds to compression in the same manner as the experimentally-prepared *in vitro* spine.

Ayoub and Mital (1989) stated that a variety of models have been developed to evaluate industrial MMH tasks, manual lifting in particular. The validation and applicability of models has resulted in an ongoing debate in various research articles (Mital **et al.**, 1997; Dempsey, 1998). For example, NIOSH (1981) recommended design standards for lifting tasks using an allowable limit of approximately 3 400 N of compressive force at the L5/S1 articulation. Several studies have more recently suggested much higher values could be observed during reasonably safe lifting (Kumar and Mital, 1992; Mital **et al.**, 1997). Following extensive research, Mital **et al.** (1997) suggested that compression forces of approximately 3 930 N could be tolerated by most males and 2 689 N by most female operators. The major caution is that compression strength should not be used a sole design criterion. Manual tasks involve a complex interaction between the worker and the object being moved. A typical complication of the manual handling process relates to asymmetrical lifting (Mital and Kromodihardjo, 1986). Asymmetrical lifts have been shown to be relatively more hazardous than symmetrical lifts in various studies due to the additional torsional stress on the spine (Davis and Marras, 2003; Marras **et al.**, 2006).

One of the major advances in understanding trunk motion characteristics has been achieved through the utilisation of the lumbar motion monitor (LMM) developed by the Biodynamics Laboratory at the Ohio State University (OSU). Various studies have been conducted to assess the accuracy and reliability of the LMM when measuring changes in position, velocity and acceleration (Marras **et al.**, 1992; Gill and Callaghan, 1996). To ensure accuracy and sensitivity of the LMM, the unit was validated by using a video-based motion analysis system in research conducted by Marras **et al.** (1992). Their research showed high correlations and significance levels ($r>0.95$, $p<0.0001$) for sagittal, lateral and twisting planes of motion. Gill and Callaghan (1996) concluded that the LMM is suitable for use in clinical and research settings when assessing range of motion (ROM) and changes in velocity. The LMM is essentially an exoskeleton of the spine in the form of a tri-axial electrogoniometer that measures the instantaneous three-dimensional position, velocity and acceleration of the spine (Marras **et al.**, 1997; Davis and Marras, 2003).

The LMM has been widely used to assess current workplace demands and calculate a risk prediction. The LBD risk model was developed in the Biodynamics Laboratory (Marras **et al.**, 1997) following an *in vivo* study undertaken to determine quantitatively whether dynamic trunk motions, in combination with workplace and environmental factors, may better describe the risk of LDB in repetitive MMH. A cross-section of industrial jobs was assessed with jobs divided into low- and high risk of LBD. By averaging moment, frequency of lift, sagittal flexion, twisting velocity and lateral velocity, the LBD risk model is able to predict the probability of high risk group membership for any repetitive job (Marras **et al.**, 1997).

Use of the LMM and associated LBD risk model has a number of advantages when adopting a biomechanical approach to the evaluation of manual work. Data from the LMM are collected instantaneously and resulting calculations of the injury risk are determined irrespective of the investigator's view of the work (Marras **et al.**, 1997). In addition, the LMM allows for the comparison of MMH jobs with a database covering a wide range of manual work. The probability model enables quantitative assessment of each sub-task within a job and the LDB risk model may assist in the ergonomic intervention process (Marras **et al.**, 1997). The LBD risk model therefore provides a useful tool for use in pre- and post-intervention investigations, as was the case in the present study. Furthermore, the LMM has been used in conjunction with an EMG-assisted biomechanical modelling (Granata and Marras, 1993; Davis and Marras, 2003; Marras **et al.**, 1999; 2006) to assess the relationship between muscular activity and trunk motions. Despite advances in methods and loading predictions, the biomechanical approach would appear to have limited applicability when used in isolation (Dempsey, 1999). Incorporating the evaluation of physiological and psychophysical parameters appears to be the preferred approach (Dempsey, 1999; Lehman and McGill, 2001; Marras **et al.**, 2006).

The Physiological Approach

Mital **et al.** (1997) stated that when a worker engages in a physical task a number of physiological responses are affected. These include metabolic energy cost, heart rate, blood pressure, blood lactate and ventilation volume. Designing tasks to ensure that the physiological response of the body will be within acceptable limits is the primary goal of the physiological approach (Dempsey, 1998; 1999). The level of acceptable EE is dependent upon the duration of the task, as EE and task duration are inversely related (Dempsey, 1999). This is of particular relevance in IDCs where extended working shifts and poorly scheduled work are common place (Scott, 1999).

Datta **et al.** (1983) argued that maintaining a stable, acceptable physiological output should reduce the onset of worker fatigue over the working shift. The setting of energy expenditure limits and utility of regression models are the two key areas developed to assess work-related activities. There are some concerns for the researcher adopting physiological methods. Mital **et al.** (1997) identified two problems associated with the design of physiologically-based criteria: specifying the upper limit of oxygen consumption as a percentage of aerobic capacity that can be sustained without undue fatigue, and deciding on what kind of aerobic capacity should be used to express the percentage. There are a number of other limitations to the utility of physiological models. Leamon (1994) stated that little association exists between cardiovascular capacity and incidence of low back pain. Low back pain has been shown to be more likely to result from cumulative load, and the establishment of manual handling guidelines based on whole body physiological responses should possibly be re-evaluated. Dempsey (1999) concurred with these findings and stated that the use of physiological measures may be limited, as the ability to differentiate LBD risk is highly limited. Of the current methods used, Dempsey (1999) suggested that oxygen consumption is the most common measure used to estimate EE.

Despite the acknowledged limitations of selected criteria used in the evaluation of the cost of manual work, a few researchers continue to use physiological methods. Physiological methods remain of particular importance in IDCs due to the vast number of rural work settings which pose unique challenges (Scott **et al.**, 2003; O'Neill, 2005). Physiological demands frequently exceed operator capabilities, with many people carrying loads well in excess of 30kg on their heads, shoulders and backs for long distances (O'Neill, 2005). Scott and Christie (2004) argued that physiological responses are influenced by the working environment, the individual and the activity. In IDCs the loads lifted are commonly excessive and necessitate poor working postures. In an attempt to address the problem of excessive work loads, ergonomists in South Africa are increasingly involved in analysis of the imbalance between worker capabilities and task requirements (Scott and Christie, 2004). Compounding the problem of heavy manual work, is the poor nutritional and health status of the majority of the working population in IDCs (Renz and Scott, 2004). *In situ* physiological assessments are more difficult to control than those conducted in a laboratory (Renz and Scott, 2004; Scott and Christie, 2004), consequently, limited research has been conducted *in situ* to predict workplace EE.

Central to the drive for productivity improvement is the challenge of finding an acceptable work rate for a given job (Bridger, 2003). Extreme whole-body motions such as required for lifting actions increase the demand for blood to transport oxygen to the working muscles (Capadaglio **et al.**, 1997; Renz and Scott, 2004). Of the physiological methods used to monitor human responses, the most frequently assessed variable in the field is probably heart rate (Scott and Christie, 2004). Heart rate may be recorded using relatively inexpensive equipment which is principally non-invasive. Various classification tables and matrixes have been developed to assess heart rate responses in the laboratory and field (Sanders and McCormick, 1993; Bridger, 2003). Renz and Scott (2004) demonstrated that a simple manual handling task involving lifting and lowering may elicit a mean heart rate response in excess of 135 bt.min^{-1}. The classification matrix developed by Sanders and McCormick (1993) suggests that a workload that results in heart rate responses between 125 and 150 $bt.min^{-1}$ is classified as 'heavy'. Setting acceptable heart rate limits is a potential area of use for moderating the physiological cost of work. Further applications of heart rate data have been widely researched (Capadaglio **et al.**, 1997; Renz and Scott, 2004; Scott and Christie, 2004; Scott and Renz, 2006). In research conducted on forestry workers in South Africa (Scott and Christie, 2004), their study demonstrated that the use of a regression equations to predict maximal oxygen consumption (VO_{2max}) from heart rate is an acceptable means of estimating energy expenditure of manual labourers where scientific expertise and equipment are not readily available.

Electromyography (EMG) is used by ergonomists to detect workspace and task factors that cause unnecessary or rapid muscular fatigue (Bridger, 2003). Lehman and McGill (2001) stated that the use of EMG and EMG modelling to evaluate current or predicted workplace demands is widespread. Various researchers have used EMG modelling to assess muscular activity in the agonist and antagonist muscle groups during MMH (Marras and Granata, 1995; 1997; Davis **et al.**, 1998; Jorgenson **et al.**, 2004). The Biodynamics Laboratory at the OSU has completed extensive studies using an EMG-assisted biomechanical model (Marras and Granata, 1995; Marras **et al.**, 1999; Chany **et al.**, 2006). Findings specific to EMG-assisted modelling are utilised in conjunction with spine loading variables and trunk kinematic responses for each participant to determine both the physiological and biomechanical loading during a given task (Granata and Marras, 1995). The model employs EMG and kinematic input to determine the dynamic, relative muscle force vectors of the ten, modelled, trunk muscles following the work of Schultz and Anderson (1981). The trunk muscles probed include the right and left *latissimus dorsi*, *erector spinae*, *rectus abdominus*, *internal abdominal obliques*, and *external abdominal obliques* (Marras and Granata, 1995; Granata and Marras, 1995). The EMG-assisted model has a major benefit in that it can provide an insight into the effects of motion induced, muscle coactivation on spinal loading (Granata and Marras, 1995). Marras and Granata (1995) concluded that the EMG model may be used to investigate the etiology of LBD and reduce the risk of occupational injury.

Torso working posture has a major influence on force generation and muscle recruitment patterns (Marras **et al.**, 1998). Trunk muscle activity has been shown to vary according to the working posture adopted and the asymmetry of task completion (Marras **et al.**, 1998). Muscle activity will vary according to a standing or flexed trunk position, and McGill (1991) argued that EMG activity of the trunk muscles have described significant muscle coactivity during twisting while standing. Under upright trunk twisting conditions, twisting torque is generated easily and efficiently with the assistance of the *oblique* and *latissimus dorsi* muscles (Marras **et al.**, 1998). However, when the trunk is flexed the activity of the *erector spinae* muscles increases while the *external oblique* activity decreases. These findings have important application in the present study where asymmetrical working postures were simulated for both the Paintshop and Bodyshop tasks.

The Psychophysical Approach

Psychophysical assessment of subjective discomfort is often used as a short-term response to biomechanical stress in order to provide guidance to the ergonomist during workstation design and evaluation (Lin and Radwin, 1998). Various psychophysical methods have been successfully used to establish maximum acceptable workloads in repetitive lifting tasks (Legg, 1981; Nicholson and Legg, 1986, Karwowski **et al.**, 1992). Workers are required to make a personalised assessment of task demands of a particular MMH job and the information gained has been utilised extensively to design and redesign MMH jobs in a variety of industries for over three decades (Ayoub and Dempsey, 1999).

Gamberale **et al.** (1987) argued that one way to prevent injuries resulting from manual handling of materials is to apply restrictions on how much an operator should be permitted to lift. Ergonomists adopting the psychophysical approach are thus required to ensure that operators are adequately trained to evaluate current and future task demands in their work areas. Nicholson and Legg (1986) referred to the design of working tasks based on the psychophysical approach being concerned with what a worker *will* do rather than what they *can do*.

There are numerous psychophysical design databases available for various MMH tasks (Ayoub and Dempsey, 1999), which frequently require a high level of worker understanding of self-pacing and self-regulation in the workplace. Mital **et al.** (1997) stated that the psychophysical approach to MMH job design requires individuals to adjust either the handling frequency, mass of the load or the force exerted on the object being handled according to their perception of physical strain. The primary goal of the psychophysical approach is to design tasks that are "acceptable" to the majority of workers performing a task (Dempsey, 1998). Workers have access to a task-specific database which allows them to select a load, force or frequency for a particular activity. One of the major concerns related to the data utilised by these databases is the short periods of time (20 – 25 min) over which much of the data have been collected. Data collected in shorter trials are acceptable for low frequency tasks, but do not apply for moderate to high frequency tasks (Mital, 1983); and Marras **et al.** (2006) demonstrated that spinal loading does not respond in a consistent or expected manner over the eight hour working shift. Guidelines based on shorter duration manual handling would therefore appear to be extremely limited in workplace application. There is also a major concern that data and methods employed in IACs are not necessarily guaranteed to work in IDCs, where the profile of the workforce is substantially different.

Snook (1985) evaluated the advantages and disadvantages of the psychophysical approach. The advantages included the following: a realistic simulation of actual task demands is completed, testing does not require a "steady state" as per physiological research designs, studies produce reproducible results; and a high level of association is observed between demanding tasks that have been subjectively rated and operator reports of low back pain. Although the approach relies on a high level of task understanding on the part of the operator, it would appear to be very useful in setting realistic working levels using the worker as the "expert". Snook (1985) also highlighted a number of disadvantages of the approach: the subjective nature of the reports can be a source of concern and criticism; the results obtained may vary substantially depending upon the frequency component of the workload, and psychophysics does not appear to be sensitive to dynamic activities which include bending and twisting. Mital **et al.** (1997) reported that the psychophysical approach, using the worker to subjectively evaluate the task demands, results in the safest working environment. The practical applicability of the psychophysical approach is not as simple in an IDC country, as the level of complexity of the task and level of education of the operator are not always matched. It is therefore up to the ergonomist to critically evaluate the working situation and utilise the most effective approach for the given industrial setting.

Ayoub and Dempsey (1999) suggested that one of the major needs in psychophysical research relates to the need for epidemiological field verification of psychophysical data. Many of the databases are in need of updating with recent quantitative analysis of industrial tasks demands for a variety of industries. Although the psychophysical approach does have disadvantages, Ayoub and Dempsey (1999) argued that the approach has been useful in reducing the mismatch between the operator and the task in many instances. In IDCs there is a still a great deal of potential for the utilisation of the psychophysical approach due to the sub-optimal task demands regularly observed. The key challenge will be to modify the psychophysical approach to the level of understanding of the workforce, particularly in those automotive industry sectors that do not have a highly educated workforce.

PSYCHOPHYSICAL RESPONSES

Each human operator responds in a unique manner to the task requirements of a given workplace. Understanding the importance of the perceptual responses of the "human factor" in the Man-machine interface is thus a major focus for the ergonomist. Increased demands and pace of manufacturing have resulted in a growing interest in the perceptions of operators towards their physical workload (Borg, 1982). Psychological factors have been shown to exert significant influences on the efficiency of performance of the worker required to complete manual tasks.

A number of methods have been developed to aid the evaluation of workers' perceptual responses. Borg's (1971) Rating of Perceived Exertion (RPE) scale and Corlett and Bishop's (1976) Body Discomfort Scale (BDS) are two of the most widely used. These scales provide a subjective evaluation of the perceived demands and discomfort associated with the task under investigation, and have been widely used to ensure that the incompatibility between the operator and the task is minimised. Mital **et al.** (1997) argued that an operator who can quantify the physical demands of a given task is less likely to exceed their personal threshold during MMH task completion.

Ratings of Perceived Exertion (RPE)

In order to quantify the responses of either the worker or the laboratory participant, Borg (1971) proposed the Rating of Perceived Exertion (RPE) scale. Borg's 6-20 RPE scale was used in the present study (See Appendix A). Borg (1982) argued that it was essential for scientists to develop methods to quantify subjective symptoms and evaluate how they related to objective findings. The Borg rating scale has been widely used in MMH risk assessment (Straker **et al.**,1997; Dawes **et al.**, 2005). The Borg RPE scale used in the present study consisted of both verbal anchors and numbers for rating purposes. Dawes **et al.** (2005) suggested that the RPE scale may be used effectively to quantify perceived exertion in instances where physiological loading increases during work or exercise. The RPE scale may also be used to assess perceived exertion using 'Central' and 'Local' ratings. 'Central' RPE requires the participant to rate perception based on cardiovascular response, while 'Local' ratings are used to evaluate localised exertion, for example, in the back or arms (Christie and Scott, 2005).

Gamberale (1985) stated that the perception of exertion during physical work not only has psychological validity, but it also reflects real conditions such as the interplay between the requirements of the task and the capacity of the human operator. Where workers are frequently required to lift or carry heavy loads, or to work under trying conditions, the psychological make-up of the operator needs to be adequately matched to the demands of the task. Perceived exertion thus has an important application in an occupational setting (Noble, 1982; Dawes **et al.**, 2005). Setting acceptable workplace limits for exertion and pain may be one of the most useful applications of RPE. Garg **et al.** (2006) argued that fatigue is not a voluntary response, and consequently what remains of importance is to establish what levels of perceived exertion and pain are acceptable and/or "safe" in the workplace.

Carton and Rhodes (1985) provided a critical assessment of the factors that influence RPE. This review outlined the physiological basis, non-physiological factors and effects of work on RPE. RPE has been shown to be highly correlated with heart rate (HR) in numerous studies (Stamford, 1976; Mihevic, 1983). Differential use of RPE has resulted in the use of the scale to allow participants to rate both Central and Local RPE in field or laboratory research. It has been argued that local factors are responsible for the most intense sensory stimulus, irrespective of the size of the muscle mass recruited (Pandolf and Noble, 1973). Recent work carried out by Wang **et al.** (2000) used the RPE scale to assess the effect of handle angle on whole-body and wrist ratings following a change in container design. As expected, lower RPE ratings were recorded during trials where the working posture was suitable for container based work and the handle angle was closer to the neutral position.

Some of the factors to consider when using the RPE scale relate to the following: time of day; effects of sleep deprivation; the age and sex of the worker; nature of the test being completed, the duration of the testing protocol; and the impact of the working or testing environment (Carton and Rhodes, 1985). The use of the RPE scale *in situ* needs to be utilised with caution, as it is imperative that the operator is clear on the requirements for the rating of exertion. Garg **et al.** (2006) recently assessed fatigue, RPE and EMG associated with short-cycle overhead work in an automotive assembly plant. This evaluation of overhead work demonstrated that hand-tool weight, posture and work duration had a significant influence on RPE, fatigue and pain (Garg **et al.**, 2006). RPE values were the highest recorded, thereby demonstrating that operator perceptions may be a useful indicator of subjective workplace upper extremity joint loading.

Body Discomfort Map and Rating Scale (BDS)

The Body Discomfort Map and Rating Scale (BDS) are adopted from the work of Corlett and Bishop (1976). The BDS is a subjective tool used to assess the discomfort of an individual in the laboratory or working environment. The body map is divided up into 27 segments so that the subject can identify the site(s) of discomfort and rate the intensity on the rating scale (See Appendix B). Cameron (1996) stated that in laboratory settings, studies using discomfort scales have been designed to increase our understanding of factors that affect the performance of tasks which occur in many different work environments. The research of Straker and co-workers (1997) demonstrated that discomfort ratings were significantly higher for tasks that required the operator to adopt an awkward working posture. Furthermore, high frequency tasks were rated greater in discomfort than the same tasks performed at lower frequency, presumably due to the onset of muscle fatigue more rapidly during the more rapid task completion. High levels of discomfort during task completion are often an indicator of risk in the workplace due primarily to the onset of fatigue or excessive task demands (Straker **et al.**, 1997).

Discomfort is primarily associated with the perception of pain, and that pain is associated with the working posture utilised, and with the effort expended (Cameron, 1996). Heavy physical work will increase the levels of reporting body discomfort (Corlett, 1990). Based on detailed observation of working practices (James, 2002a; James and Scott, 2006), existing rest schedules used in the automotive sector may not be sufficient to allow adequate recovery from mild to extreme body discomfort associated with poor working postures and sub-optimal task design. To this end Corlett (1990) argued that body part discomfort data should be collected at regular intervals during the working shift when used *in situ*. He further suggested that recovery from static work is usually slow and may in all likelihood not be achieved in a short rest break. It remains critical for each plant using intervention strategies based on sound ergonomics principles to assess the current task demands and to be guided by the subjective discomfort responses of the workforce while minimising the likelihood of inadequate rest periods.

Workplace Injuries and WMSDs related to MMH

General Overview

Injuries associated with MMH are widely acknowledged as a being a substantial problem, the reduction of which is a major challenge for ergonomists (Straker **et al.**, 1996). Marras **et al.** (1999) stated that the accurate identification of high risk jobs is the first step in developing an effective control programme. IDC workplaces put the operator at high risk of injury due to sub-optimal working conditions and high levels of physically demanding work. The guiding principle of human performance improvement is to balance work demands with worker abilities and needs to maximise performance measures (Shoaf **et al.**, 2000). Despite a realisation that WMSDs are a major concern, both in terms of human and monetary cost, Marras (2004) stated that research still has a long way to go before there is enough knowledge to eradicate these disorders from the workplace.

Kumar (2001) contended that workplace musculoskeletal injuries are broadly divisible under two categories: idiopathic and traumatic. The idiopathic injuries cannot be assigned to a specific work-related incident, and could well be confounded by other task-based factors. In contrast, the traumatic injuries can usually be related to a particular event or action in the work process. There are a number of risk factors which require attention when considering the South African automotive industry. Kumar, (2001) proposed that risk factors can be assigned to one of four principle groups associated with the worker as follows: genetic, morphological, psychological and biomechanical. The interplay between these factors will play an important role in determining the risk in any given industrial setting while Marras (2000) listed the following risk factors in the workplace: heavy physical work; lifting and forceful movements; bending and twisting; whole-body vibration; and static working postures. Many of these risk factors are frequently witnessed in the South African automotive industry. A further potential risk factor identified over the past decade is that of psychosocial concerns (Marras, 2000). Operators working in the automotive sector are subjected to escalating demands due to increases in production targets within a changing political environment. The psychosocial factor is therefore of great importance when considering an IDC setting, such as South Africa.

The increasing disability of musculoskeletal problems and associated cost in IACs has resulted in a call for effective preventative strategies (Viikari-Juntura, 1997). There is a need for research focusing on WMSDs due to the vast scale of this international problem. For example, in the United Kingdom 12.3 million working days are lost each year due to WMSDs (Whysall **et al.**, 2004). The future trends in the area of WMSD research would appear to indicate the desperate need for a holistic approach to the problem (Dempsey, 1998; Marras, 2004). The assessment of WMSDs may be best achieved through well-designed epidemiological studies with quantitative assessment of physical exposures and unbiased measurement of exposure-responses relationships for various industries (Viikari-Juntura, 1997). Many researchers have previously attempted to address selected elements of workplace disorder causality with very limited success. The development of a conceptual, integrated approach to guide the investigation of WMSDs is a major challenge that requires a clear research focus (Marras **et al.**, 1999; Marras 2004). A single factored approach will provide an indicator of basic risk exposure, but may ultimately result in oversights of critical risk factors in the workplace, which may increase the prevalence of WMSDs.

Work-Related Upper Limb Disorders (WRULDs)

Work-related upper limb disorders (WRULDs) remain a problem in the workplace in both developing and developed areas (Huisstede **et al.**, 2006). The significant incompatibility between the operators' capabilities and the task requirements in IDCs results in increased workplace risk. Poor working postures as the result of poorly designed workstations are often leading indicators of WRULD likelihood. One of the major concerns with respect to WRULD reporting and control relates to the lack of standardised measures and associated assessment criteria (Buckle and Devereux, 2002). The current level of understanding is inconsistent with a lack of standard procedures and lack of expertise for the diagnosis of WRULDs. From the information which is currently available for the European Union, the most common areas for WRULDs are the shoulders followed by the wrists/hands and finally the elbows (Buckle and Devereux, 2002). In addition, Muggleton **et al.** (1999) reported that WRULDs rank second to back complaints in the United Kingdom. In the South African industrial setting there remains a substantial amount of work to be done on the establishment of understandable statistical reporting with regards to WRULDs.

There exists a clear need to assess the upper limb postures adopted by a number of operators in the automotive assembly process due to the handling of awkwardly shaped vehicle parts, panels and tools. Risk factors for upper limb disorders are poorly understood due to a lack of large, robust cohort studies that include clearly defined health outcomes and objectively measured work exposures (Garg **et al.**, 2006). Colombini (1998) argued that the four main risk factors to consider when assessing the upper extremity and likelihood of WRULDs are: repetitiveness (and associated frequency); force application; awkward working posture and movements; and the lack of overall recovery time during the work cycle. These concerns are verified by *in situ* analyses of the South African automotive environment, where risks to the worker are clearly evident, particularly in the Bodyshop and Trim Lines. The presence of a repetitive lifting task for the upper extremity can be defined as the consecutive activity, lasting at least one hour, in which the operator carries out work cycles similar to each other and of relatively brief duration (Colombini, 1998; Muggleton **et al.**, 1999; Buckle and Devereux, 2002). Spot-welding and hand-gun operation are industry-specific examples of upper extremity dominated tasks that increase the likelihood of WRULDs. Repetitive carriage of vehicle panels, for example car doors, may also lead to increased reporting of upper limb problems. Upper limb pain may arise from discrete pathological conditions, such as adhesive capsulitis, rotator cuff tendonitis, lateral epicondylitis and tenosynovitis, or as part of non-specific regional pain syndromes (Palmer **et al.**, 1998).

Muggleton **et al.** (1999) stated that there are a range of factors which are known to or thought to contribute to WRULDs, both occupationally-related and non-occupational. Among the key broad categories, these authors listed load-related; posture-related; and environmental factors as being contributors to upper limb problems. Upper-extremity dominated tasks, such as vehicle parts carriage, spot-welding and hand screw gun operation, can be observed in all South African automotive industries. Tool use primarily requires consideration of the force, posture and time components of the task (Kadefors and Sperling, 1998). Seth **et al.** (1999) suggested that cumulative trauma disorders (CTDs) typically affect the operator required to carry out tasks dominated by use of the upper extremities. Many of the common problems are related to the poor working postures adopted *in situ*. Seth **et al.** (1999) cautioned that working postures adopted in the manufacturing process are important as awkward movements increase the rate and likelihood of localised and general fatigue. This is particularly relevant to the car door carriage area of the Bodyshop where awkward postures and carriage of heavy loads predominantly using the upper extremity are commonplace.

Posture-related factors are frequently the most commonly cited risk factors for cumulative trauma disorders of the upper limb (Armstrong, 1996; Muggleton **et al.**, 1999; Gallagher, 2005; Garg **et al.**, 2006). The common activities of lifting or lowering, carrying, and pushing or pulling necessitate predominant use of the upper limb in moving a load from point-to-point. Wrist flexion/extension, radial/ulnar deviation, elbow movement and shoulder movement are key areas for consideration in the assessment of upper limb work actions. Working with the arms raised poses a number of problems in the workplace (Muggleton **et al.**, 1999; Garg **et al.**, 2006), and may lead to discomfort if not eliminated during the evaluation and redesign of workplace logistics. Palmer **et al.** (1998) reported that shoulder pain is often manifested in the deltoid region and will be felt during resisted active movements. Both the Paintshop and Bodyshop areas evaluated in the present study raised concern for the workers due to the task demands. These areas clearly require redesign aimed at eliminating the high risk of WRULDs currently prevailing in the automotive plant.

LABORATORY AND *IN SITU* EVALUATIONS

Current Trends

There is a growing debate in ergonomics about the relative advantages and disadvantages of laboratory and field investigations (Scott and Christie, 2004). Laboratory based research in ergonomics is abundant, with various studies conducted to assess biomechanical, physiological, psychosocial and epidemiological consequences of human work. The rigorous control of laboratory experimentation allows for more accurate information with respect to identifying the incompatibilities between the task and the human operator, where conditions can be more easily controlled than when working in the field (Scott and Christie, 2004; Renz and Scott, 2004; James and Scott, 2006). However, laboratory test results do have a number of limitations when considering "real world" applications where extraneous variables may have a substantial impact on this interaction between the two key components (Renz and Scott, 2004). The relevance and potential application of findings of laboratory work needs to be carefully considered before use *in situ*. Laboratory based findings are not always directly applicable due to the complexities of the workplace, where a number of external factors, for example, environmental extremes, noise and inconsistent work patterns, may affect work performance (Scott and Christie, 2004).

Furthermore, Scott and Renz (2006) argued that artificial reconstruction of a work situation within the sterile environs of a laboratory renders the relevance of the findings to "real world" situations highly questionable.

The Need for Laboratory and Field Work in IDCs

Researchers have argued that the main drawback with field work is the lack of control over experimental circumstances (Oborne, 1995). However, previous studies have highlighted the importance of practical application of laboratory findings in the field (Zalk, 2001; Scott and Christie, 2004; James and Scott, 2006). Ergonomics is after all an **applied** science, and while rigorous work-related research conducted in laboratories is essential for the advancement of the discipline, unless more attempts are made to link laboratory and field work, the good theoretical work being conducted in the laboratory remains esoteric and in the main not applied in industry (Scott and Christie, 2004). In addition, Scott and Renz (2006) argued for the need to integrate laboratory and field research in the discipline of ergonomics. Consequently, the field evaluation of automotive tasks should allow for the identification of key problem areas within this sector (James, 2002a; c). The automotive industry in South Africa, which is currently in a very strong growth phase spurred by foreign investment and the MIDP, is in desperate need of the application of basic ergonomics *in situ*. The need for practical application of basic interventions is unquestioned, hence the great need for further “field-laboratory-field” studies (James and Scott, 2006; Scott and Renz, 2006).

CONCLUSIONS

The Potential Role of Participatory Ergonomics (PE) in IDCs

Participatory ergonomics (PE) has been suggested as an effective intervention strategy to simultaneously address risk factors in the workplace (Theberge **et al.**, 2006). The development of PE programmes within IDC industry has potential for rapid expansion. Wilson (1994) stated that the requirements that any organisation might have for ergonomics input are many and varied. Simply implementing an ergonomics intervention strategy without looking at the overall needs of the organisation would be detrimental. There exists a need to focus on the “human factor” and at the same time assess the role of company management in the programme. In South Africa this is still largely misunderstood and only one of the major automotive organisations currently employs an ergonomist (James and Scott, 2006).

A programme specifically aimed at meeting the needs of IDC industry is therefore required as a starting point for planning ergonomics intervention strategies. According to Wilson (1994) there are three aspects which are required in the implementation of a successful ergonomics programme. Firstly, the ergonomics programme should not be seen as a cost, but as a vital component of the value adding activities of the company. Secondly, the company must be able to accept participative culture and utilise participative techniques. The third aspect is that ergonomics-related problems must not be seen purely in engineering terms. Many South African industries currently approach ergonomics purely from the engineering perspective, and this has led to various problems for the end user.

The participatory approach has been shown to be most successful in ensuring a change in workplace behaviour (Scott, 1997; Kogi **et al.**, 1998; Theberge **et al.**, 2006). In the South African automotive industry there appears to be a specific need to ensure that the participatory approach is adopted to allow operators to understand the reasons for change before the implementation process commences.

Ergonomics Facilitation Teams

Scott (2001) argued that all role players should be encouraged to become part of the process of implementing ergonomics via participation in a "Facilitation Team". Assessments of the automotive working environment by Fredriksson **et al.** (2001) demonstrated that the manner in which changes are implemented has an impact on the success of ergonomics interventions. This research suggests that manufacturing plants should pay greater attention to psychosocial aspects when workplace changes are planned and implemented. This consideration is of vital importance in IDCs, such as South Africa, where psychosocial factors are a major influencing factor in determining the approach of an individual towards an intervention. Many employees in the automotive industry have only a very basic level of education, and the level of complexity of awareness sessions and reading materials has to be considered within that framework.

The current trend in the automotive industry highlights a reactive rather than proactive response to immediate and obvious problems, with little attention given to establishing a production line running on sound ergonomics principles. Establishing effective Ergonomics Facilitation Teams in these manufacturing plants is one area which could assist in the reversal of this trend. There is a need to increase the frequency of ergonomics surveys conducted to assess the Man-machine interface. Ergonomics workshops need to be conducted to train employees in hazard identification. Training needs to highlight the necessity to be proactive in dealing with potential work-related hazards. The process of implementing ergonomics needs to be participatory and involve “co-operative, co-responsibility” (Scott, 1996) on the part of the key personnel.

CHAPTER THREE
METHOD

INTRODUCTION

The South African automotive industry is comprised of a number of component industries and seven manufacturing plants. Visits to a cross-section of plants were completed during the initial phase of the present study. These visits assisted in the identification of work-related hazards currently affecting the overall health, safety and efficiency of the human operator working in this sector. Laboratory simulations were then conducted following the *in situ* identification of high risk tasks. In the automotive industry there are a number of manual handling tasks which require urgent assessment of the compatibility, or lack thereof between the industrial worker and the job requirements. These assessments were completed in a manner that allowed for the effective quantification of specific task demands taking into consideration the biophysical, physiological and perceptual demands placed on the workforce in order to take a holistic integrated approach to the assessment of human responses as proposed by Charteris **et al.** (1976).

Following a general observation period and feasibility studies conducted in various manufacturing plants throughout South Africa, the General Motors plant (GM, Struandale in the Eastern Cape) was selected as the focus for further investigation. Detailed field assessments were then completed prior to the laboratory testing sessions which served to familiarise the researcher with the general set-up of manufacturing operations, sub-tasks completed, current workflow, work methods and the workers themselves. It also aided in identifying high risk tasks that would require investigation and were in need of ergonomics intervention. Interviews and strategy meetings were conducted with personnel from GM Struandale Plant Engineering and the Safety, Health and Environment (SHE) sections, who answered questions regarding organisational issues, such as current working shifts, production demands, worker incentives, and future plans and expansion in the GM Struandale plant. Thereafter, basic measurements of workspace dimensions, task requirements, plus the workers' demographic and anthropometric characteristics, heart rate, activity count and perceptual responses were recorded *in situ* in order to identify and prioritise problem sub-tasks identified in the Paintshop and Bodyshop areas.

FIELD OBSERVATION

Field Task 1: Paintshop Area

The GM Paintshop exhibits a high prevalence of pushing and pulling activities with heavy vehicle frames being moved during the course of the working shift. These tasks require the worker to complete one and two-handed pushing or pulling actions to move the units on transfer trolleys in this area of the assembly plant (see Appendix B for an example of an *in situ* task analysis sheet). Figure 4 a to d highlight the four principle actions identified during the field investigation.

a *One-handed Pull*

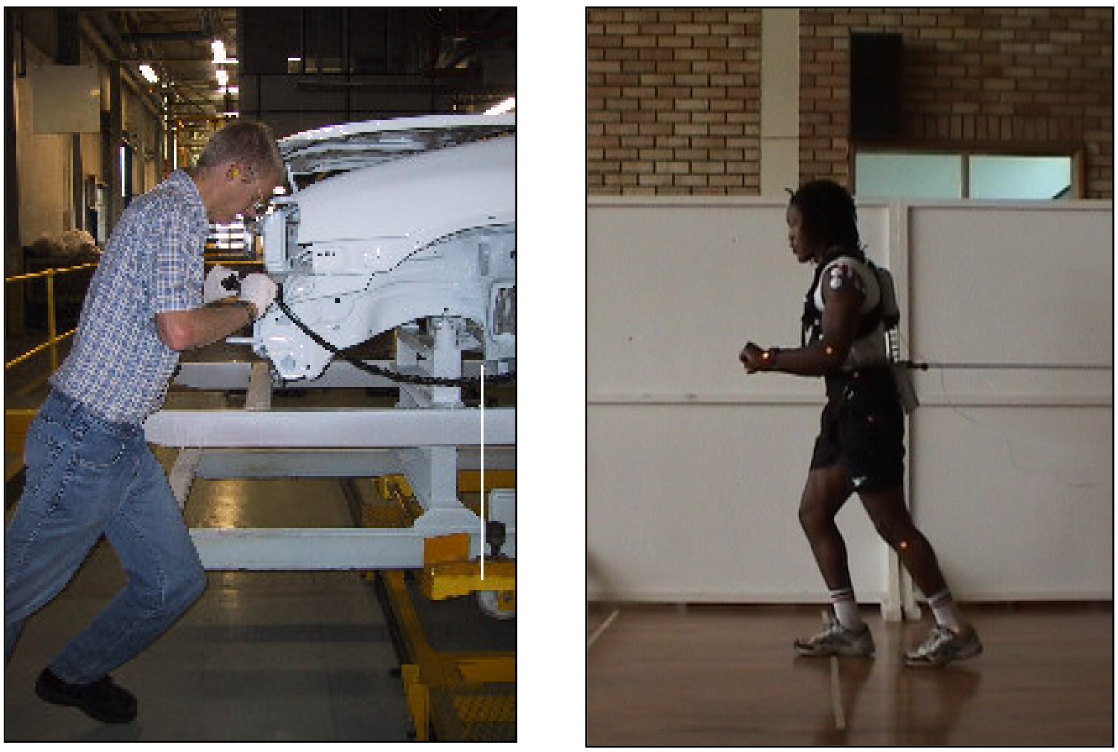
b *Two-handed Pull*

c *One-handed Push*

d *Two-handed Push*

Figure 4 a, b, c and d: *Paintshop workers complete selected sub-tasks required during the working shift.*

The *in situ* push-pull evaluation aimed to assess the pull and push forces required to complete a series of sub-tasks (see Figure 4 a to d) in the Paintshop. *In situ* analyses were conducted to assess both the forces required to move skid units (a metal platform that carries the vehicle unit) onto a "trolley-based" platform, and then onto a "roller-based" conveyor line. Push-pull forces were assessed using a Chatillon™ Hand-Held Dynamometer (Model CSD 500) following a standardised protocol. Repeated measures were recorded for three different models of vehicles in the Paintshop (see Figure 5).



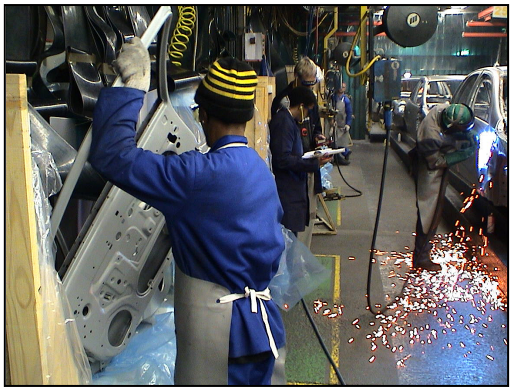
a b

Figure 5 a and b: *In situ force evaluation using the Chatillon™ Hand-Held Dynamometer (Model CSD 500) in the GM Paintshop (a) and the laboratory simulation of the Paintshop two-handed pushing action (b).*

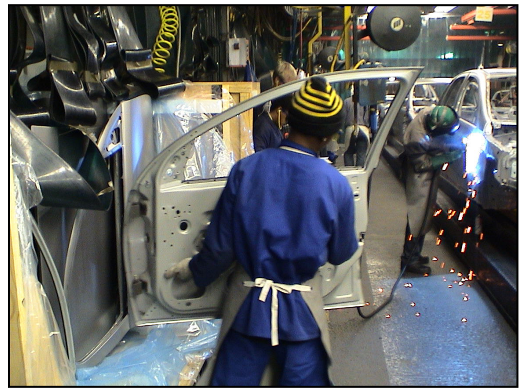
James and Todd (2003) reported that push-pull evaluations demonstrated that a change in the model of vehicle moved differentially taxed the operators working in this area. The heaviest model placed significant strain on the worker, requiring them to work at 95% of their maximal whole-body pull force, while the push forces were determined at 78% of maximal push force. Furthermore, the awkward postures required by the operator while pushing and pulling increased the likelihood of musculoskeletal injuries (MSI), and of slip, trip and fall (S, T and F) incidents. Based on the research conducted by James and Todd (2003), the measurement of push-pull forces was completed in the field during follow-up work for the present study. Force requirements were evaluated for three different vehicle units with the “worst-case” model used to determine the force output required during the laboratory pushing and pulling simulations. The value assigned for the laboratory testing was 20kg.f (mean value recorded), which was determined to be representative of the output required during the movement of the skid in the Paintshop during the sub-task pushing or pulling the heaviest model.

Field Task 2: Bodyshop (Closure Line) Area

The automotive Bodyshop is an area which is characterised by high noise and temperature levels (particularly in the hot summer months) due to the welding operations that take place in this confined area. A large amount of manual work is still completed on the Closure Lines of South African automotive plants. The manual activities include the carriage of car doors, which are heavy, awkwardly shaped and difficult to manoeuvre. The incidence of MSI as a result of load carriage is high in these areas, particularly in the form of upper extremity injuries. In addition the majority of the work-related incidents in the Bodyshop relate to some form of hand or finger injury due to the sharp edges of the vehicle frames carried on the Bodyshop Closure Line (Visser, 2004 and Khumalo, 2004). Figure 6 a, b, c and d highlight the principle working sub-tasks identified during the field investigation in the Closure Line area of the plant. The focus of the present study was the door lift, carry and placement sub-tasks. Additional sub-tasks in this area were completed with the assistance of mechanical hoisting devices (MHDs), and therefore did not require substantial physical effort on the part of the worker. The primary concerns relating to the current Bodyshop task demands were identified as follows: the step into and out of the storage bin to collect the required door; the sharpness of the metal edges of the doors; the space confinement placed on the operators due to the “protective curtains” and overhead jigs in the Closure Line; and the physical load carriage requirements of completing a working shift carrying doors with a mass of up to 20kg (front doors).



a *Lifts the car door from the crate*



b *Twists and carries door from the crate on the Closure Line*

c *Carries the door from storage approximately 3 to 5m*

d *Places the door on the hoisting jig*

Figure 6 a, b, c and d: *Bodyshop operators complete the lifting, carrying and placing manual tasks on the Closure Line of the GM Struandale plant.*

PILOT RESEARCH

Preceding the laboratory experimentation phase, preliminary and pilot studies based on the initial field evaluations in the GM plant, were conducted in the Ergonomics Laboratories of the Department of Human Kinetics and Ergonomics at Rhodes University. These initial simulations of the selected automotive tasks served to refine the testing protocol and establish the suitability of the equipment to be used and the variables measured. The main focus during these pilot studies was determining the set-up and duration for the two experimental conditions used to simulate the Paintshop (Task 1) and Bodyshop (Task 2) activities.

Four male subjects participated as volunteers during the pilot testing. Testing was conducted in two laboratory areas set up to simulate the push-pull of the car frames, and car door carry conditions respectively. Firstly, the push-pull task was assessed to ensure that the method was feasible for testing a large group of participants. Initially a value representing the highest peak force was to be used for the PTT simulation. However, the peak forces collected during the field evaluation were highly variable (range 18.5 to 45.7kg.f) due to factors including the position of the skid unit, the maintenance of the tracks, and the positioning of the worker during the pushing or pulling of the unit. Consequently the load was standardised at 20kg.f based on the current workplace demands. The distances simulated in the laboratory were also standardised to *in situ* measurements for each of the push-pull sub-tasks. During the pilot work it was established that three repetitions per sub-task (18 repetitions completed in total) would be sufficient to ensure that the participant was able to complete the task efficiently, but without undue fatigue. The RPE scale (Borg, 1971) was used originally in the push-pull pilot evaluation, but upon due consideration it was felt that the scale would not offer an accurate reflection of the ratings of exertion due to the short time duration of the testing. The RPE scale was therefore substituted with a Body Contribution Map and Rating Scale (adapted from Corlett and Bishop, 1976; see Appendix C). This scale allowed participants to make perceptual ratings of the areas of greatest contribution during the push-pull tasks, and thereby identify the areas of the body which they felt were the most significant contributors during the pushing or pulling efforts in the PTT laboratory simulation. The Body Contribution Map and Rating Scale were developed in the Department of Human Kinetics and Ergonomics at Rhodes University during isometric and isokinetic pushing and pulling research (James **et al.**, 2005). The Body Contribution Rating Scale required participants to rate the perceived contribution of a specific body area, and then rate the effort from 1 – 10, with 10 representing maximal muscular contribution. The Body Contribution Map and

Rating Scale were shown to be a useful indicator of the key areas of muscular involvement during this research. James **et al.** (2005) argued that the Body Contribution Map and Rating Scale may be used as a perceptual indicator of the areas that are most likely to be excessively strained in the event of physically taxing pushing and pulling activities in laboratory and industrial settings.

The car door carriage simulation involved a detailed pilot test assessing the feasibility of the pre- and post-intervention methodologies. The pre-intervention testing was used to evaluate the work cycle time and carriage distance specifications as per the field investigation. The wooden storage bin (supplied by GM) was also placed at the measured height to ensure that the step in was the same as the current field requirements. In an attempt to simulate the constricted working space of the Bodyshop, a barrier was placed in the laboratory and a demarcated walking path placed on the floor during the pilot phase of testing. The post-intervention pilot work required a detailed assessment of the feasibility of the transfer trolley designed and constructed in the Department of Human Kinetics and Ergonomics. The pre- versus post-intervention comparisons were sought through the maintenance of a work cycle consisting of one door carry every 30s. This was established through moderate paced pushing of the trolley and a clear method of task completion on the part of the participant. The post-intervention trolley push was clearly verbalised and practised for each pilot subject, as testing revealed that the completion of the intervention task required methodical and moderate paced work. The full kinematic, EMG, heart rate and perceptual responses for the pilot testing will be clarified in Chapter Four.

EXPERIMENTAL DESIGN

Laboratory experimentation of the selected industrial working operations included two independent experimental tasks (1 and 2) for both the push-pull of the vehicle frame and car door carriage tasks. The existing industrial scenario was simulated during Condition A (pre-intervention), while Condition B (post-intervention) assessed the effect of the proposed ergonomics intervention following the identification of the major problem areas for each of the two independent tasks.

Task 1: Paintshop Trolley Transfer (PTT)

The laboratory set-up was based on the data collected within the automotive industry. The Paintshop simulation (Task 1) was set up to allow for the assessment of the four activities observed in this area of the plant and the two proposed interventions. The PTT tasks included the assessments outlined in Table I.

Table I: *Basic set-up of laboratory Task 1: PTT assessment. (n = 30)*

Action	Pre-Intervention (Condition A)		Post-Intervention (Condition B)
Pushing	i. One-handed (20kg.f) Simulating an asymmetrical push with one hand	ii. Two-handed (20kg.f) Simulating an asymmetrical push with two hands	iii. Two-handed *Intervention* (20kg.f) Simulating a symmetrical push with two hands proposed for pushing the front of the vehicle unit
Pulling	i. One-handed (20kg.f) Simulating an asymmetrical pull with one hand	ii. Two-handed (20kg.f) Simulating a symmetrical pull with excessive lean using two hands	iii. Two-handed *Intervention* (20kg.f) Simulating a symmetrical pull with two hands on a simple rope used as an intervention

The same working heights for pushing and pulling and peak force outputs measured in the GM Struandale Paintshop during the fieldwork phase were used in the laboratory push-pull experimentation. Testing order was randomised during the laboratory phase with participants alternating between the pushing or pulling conditions at the start of testing.

Task 2: Car Door Carriage (CDC)

The Bodyshop Closure Line simulation (Task 2) required the laboratory participants to complete the Corsa (Gamma) door lift, carry and place as observed in the Bodyshop Closure Line area of the assembly process. The wooden storage crate, vehicle doors and door "jig" dimensions were provided by General Motors (GM Struandale Plant, Port Elizabeth) to allow for accurate simulation in the laboratory. During Task 2 (Condition

A: pre-intervention) participants were required to cover the same carrying distance as measured *in situ* and work at the same pace as recorded in the Closure Line. The doors carried were identical to those moved in the plant. Theoretical prediction models, including the Ohio State University (OSU) low back disorder (LBD) risk model (BIOMEC®Inc., 2002), 3-D Static Strength Prediction Programme (3D SSPP, University of Michigan Center for Ergonomics, Version 4.3.7), and LIFTRISK (Department of Human Kinetics and Ergonomics, Version 3) were also used in the development of the intervention strategies.

The set-up for Condition B (post-intervention) testing involved the movement of the vehicle door on a handling device in the form of a door transfer trolley designed in the Department of Human Kinetics and Ergonomics. Figure 7 highlights the changes to the working task proposed under post-intervention conditions.

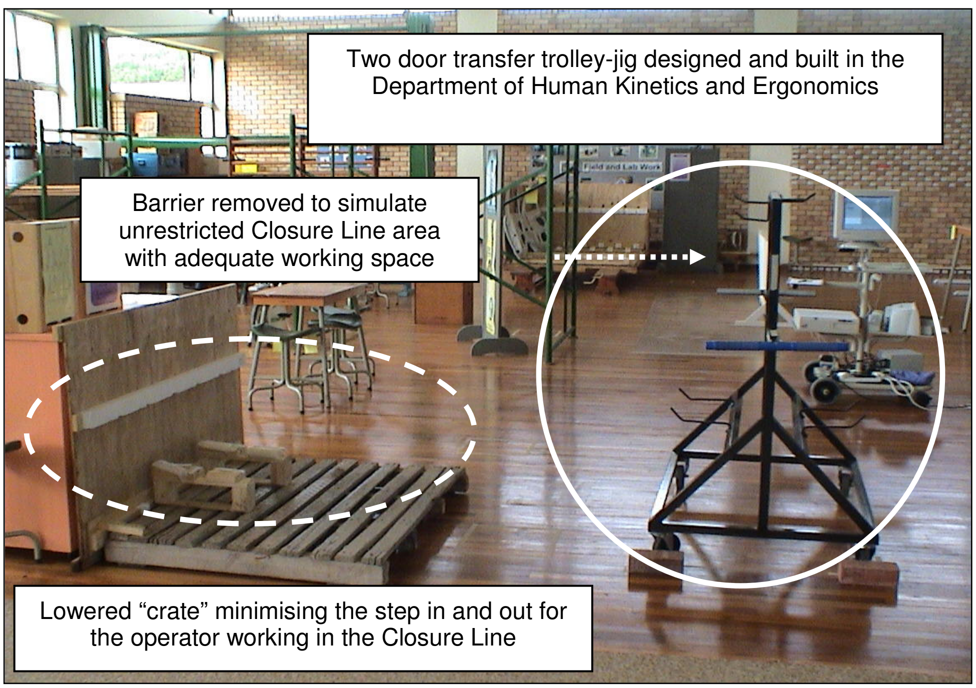


Figure 7: *Laboratory set-up for the lift, carry and placement of the car door showing proposed post-intervention changes.*
(Task 2: CDC, Condition B)

The volunteers were required to complete a second testing bout which entailed the following changes: the horizontal reach factor (H-factor), which is a measure of the distance of the hands away from the mid-point of the ankles (Waters **et al.**, 1993), was decreased from 900mm (medium reach) to 450mm (close reach), the height was lowered to pallet level (150mm) to allow for an easy step up and into the industrial storage bin, and the physical carriage of the door over 6.50m was replaced by a wheeled transfer trolley push. The work cycle time was kept constant in order to ensure that the industrial workers would still complete the task in the given time.

The two door transfer trolley was designed and built in the Department of Human Kinetics and Ergonomics using "low-cost" materials and provided with easy-moving wheels (supplied by GM) to allow for simple movement and ease of transferring the door from the storage bin to the welding jig. The trolley handles were fitted with non-slip grip and jigs were provided for both the front and rear doors on the transfer trolley. The reach factor was minimised by placing the trolley in close proximity to the simulated crate. The crate was also placed at pallet height (150mm) to eliminate the need for a large step in and out as was the case for the observed method of task completion in the field.

Table II: *Basic set-up of laboratory Task 2: CDC assessment. (n = 30)*

CDC Pre-Intervention (Condition A)	i. Step into bin, lift door and step out Simulating the current door lifting requirements from the raised storage bin in the Bodyshop	ii. Turn and carry the door past a simulated obstruction Simulating the confined working area in the Bodyshop	iii. Turn and place the door on the simulated jig Simulating asymmetrical placement of the car door on the spot welding jig as observed in the Bodyshop
CDC Post-Intervention (Condition B)	i. Step into storage bin, lift door and step out Simulating a pallet level lift of the car door in the Bodyshop	ii. Turn and place the door on transfer trolley and push along "line" Simulating an alternative method of moving the door in the Bodyshop	iii. Turn and place the door on the simulated jig Simulating a closer placement of the door in the Bodyshop from a convenient height on the transfer trolley in the Bodyshop

Tracking of physiological responses was again continuous during the experiment, whereas iLMM and EMG results were obtained at selected times during the task (min3, min6 and min9). RPE ratings were obtained from participants for Central and Local (alternating between back and arms) responses on a regular basis (Central every minute and Local alternating every second minute). The body discomfort map and rating scale was used to record any areas of discomfort or pain at the end of the 10min experimentation.

PARTICIPANT CHARACTERISTICS

Field testing and laboratory experimentation was conducted with two different groups of participants involved in the independent testing protocols. Although no medical examination was conducted, the automotive industry operators claimed to be free of injury or illness on the day of testing in the automotive manufacturing plant.

Operators were required to wear Polar™ heart rate monitors to obtain 'reference' and 'working' heart rates. While RT3 accelerometers (Stayhealthy Inc., Monrovia, CA) were used to assess the activity count and caloric output of the automotive industry workers, and these data were then used to predict the current energy expenditure (EE) of the Paintshop and Bodyshop workforce. The RT3 measures acceleration in the anterior-posterior (x), mediolateral (y), and vertical (z) axis and summarises that information as a vector magnitude (Stayhealthy Inc., 2004). The vector is calculated as the square root of the sum of the squared accelerations for each direction. Activity counts are then derived for each direction. Thereafter, activity calories per minute were calculated using the following prediction formula: [(activity counts/10) x (body mass x 1.692)]/10,000 (Stayhealthy Inc., 2004). Activity calories were subsequently converted to kilojoules per minute ($kJ.min^{-1}$) using the multiplication factor of 4.2 (Stayhealthy Inc., 2004) and then extrapolated to kJ per hour and kJ per shift.

For the laboratory experimentation, male students between the ages of 18 and 23 years volunteered to participate. The following basic and anthropometric data were recorded: age, stature, body mass, acromial height, stylion height, trochanteric height, grip strength and back strength (see Table III). No medical examination was conducted, but the participants reported no history of low back pain or current musculoskeletal discomfort that could put them at risk or present any limitations to the study.

Table III: *Basic demographic and anthropometric data of industry workers (n=12) and laboratory participants (n=30).*

	Industry Workers			Laboratory Participants		
	Mean	SD	CV	Mean	SD	CV
Age (yr)	32.42	9.51	29.34	20.40	1.22	5.98
Experience (yr)	6.54	4.57	69.88	-	-	-
Body Mass (kg)	73.75	12.60	17.08	77.82	8.17	10.50
Stature (mm)	1737	55.18	3.18	1804	44.53	2.47
Body Mass Index (BMI)	24.39	3.55	14.56	23.88	2.02	8.47
Acromiale Height (mm)	1411	60.61	4.29	1420	41.27	2.91
Stylion Height (mm)	812	36.76	4.53	825	32.15	3.90
Trochanteric Height (mm)	814	31.01	3.81	867	25.34	2.92
Span (mm)	-	-	-	1794	61.51	3.43
Back Strength (kg.f)	90.25	25.31	28.04	135.40	30.13	22.26
Grip Strength: Dominant (kg.f)	45.33	6.98	15.41	53.67	9.54	17.77
Grip Strength: Non-Dominant (kg.f)	45.50	5.95	13.07	52.47	9.38	17.88

BMI = Body Mass (kg) / $Stature^2$ (m);
SD = standard deviation;
CV = coefficient of variation (%).

ETHICAL CONSIDERATIONS

Informed Consent

Industrial workers and student laboratory participants were provided with detailed information relating to the nature of the research. In the case of the automotive operators this was verbally translated into Afrikaans (when required), and verbal and written consent were given. Student volunteers for the laboratory experiments gave their verbal and written consent to the research protocol (see Appendix A). The research protocol was approved by the Rhodes University Ethics Committee prior to the commencement of field and laboratory investigation.

Privacy and Anonymity of Results

All participants were guaranteed the privacy and anonymity of results at all stages during the present investigation. A simple data coding system was used to ensure that responses were not traceable to the workers and students. The name field was merely used for record purposes and participants were informed that the respective sets of data would be held on file for statistical analyses and future research related work.

EQUIPMENT AND EXPERIMENTAL TREATMENTS

Mirka **et al.** (2000) strongly recommended that the identification of high risk sub-tasks in industrial settings requires advanced assessment tools, particularly in occupations with highly variable biomechanical demands. In order to complete a detailed task analysis, dynamometry and telemetric heart rate monitoring equipment were utilised; however, tape measures, response counters and stopwatches were also used during the field investigation phase of the present study. Scott and Renz (2006) suggested that problems identified *in situ* should be rigorously analysed within a controlled laboratory setting and appropriate intervention strategies proposed and implemented back in the field, more often than not with minor or even substantial modifications where necessary, and then reassessed to ensure that these interventions have indeed contributed to improving working conditions.

ANTHROPOMETRIC PROCEDURES AND METHODS

The following section describes the anthropometric variables deemed necessary for the current project. A good understanding of anthropometric measurements allows for the design of equipment or tools to suit the human operator; for example, acromiale or shoulder height is an important measure in determining the position of fixtures and controls in the workplace (Oborne, 1995). Basic anthropometric data for participants are presented in Table III, Page 67.

Body Mass

The body mass of the automotive industry workers was measured to the nearest 0.5 kg using a portable Seca scale. Mass values for laboratory participants were measured to the nearest 0.1 kg using a Toledo Scale which was calibrated prior to use. Operators were weighed wearing their GM issue work clothing, whereas the laboratory participants wore light comfortable clothing.

Stature

Stature (mm) of the industrial workers was obtained using a tape measure. Laboratory subjects were measured using a Harpenden stadiometer. All subjects were required to stand upright and barefoot with their heels against the tape measure secured on a wall in the plant or the stadiometer in the laboratory, and the head erect with the subject looking ahead. Stature was measured from the floor to the vertex in the mid-sagittal plane.

All anthropometric height measurements were recorded using a functional anthropometer.

Acromiale Height

Acromiale height (mm) was measured from the floor surface to the most lateral point on the superior surface of the acromion process, with the subject standing erect and the upper limbs pendent.

Stylion Height

Stylion height (mm) was measured using the styloid process as the anatomical reference point. The most distal part of the styloid process of the radius of the arm was measured with the arm relaxed and pendent.

Trochanteric Height

Trochanteric height (mm) was recorded via the palpation and measurement of the most superior point of the greater trochanter of the femur. As this point is not easily located, participants were required to adduct the lower extremity to allow the researcher to locate the anatomical landmark.

Following the location of the correct anatomical area the participants returned to the standing erect position and the reading for trochanteric height was recorded.

Span (Laboratory Testing Only)

During the laboratory familiarisation sessions the recording of the measure of span was completed for all volunteers. Pheasant (1996) defined span as the maximum horizontal distance between the fingertips when both arms are stretched out sideways.

The measurement of span allows for practical application in determining the lateral reach of the participant. The measure of span was used to assess the percentile of maximal lateral reach that the subject was required to work at while completing the car door carriage task. Figure 8 shows the recording of span on a male subject during familiarisation in the laboratory.

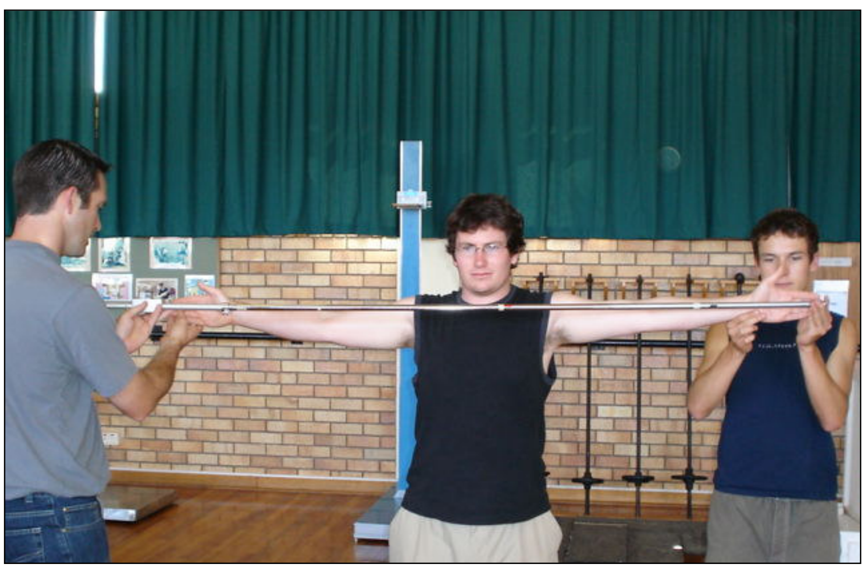


Figure 8: *Span measurement in the familiarisation session.*

PHYSICAL PARAMETERS

Strength Assessment – Isometric Dynamometry

Strength is an important factor in determining the readiness of a working cohort for manual tasks. In the case of the automotive industry where operators are required to move vehicle frames and carry car doors, grip strength and back strength measurements were deemed to be essential. Grip strength recordings were taken using the Smedley Spring hand grip dynamometer (Vacumed, Ventura, CA). For back strength responses the Takeikiki (Kogyo Co. Ltd.) back and leg strength dynamometer was utilised.

Two recordings of grip strength were obtained for each worker (dominant and non-dominant hands) in order to ensure a maximum reading. Standardised procedures for measuring grip strength included adjusting the hand grip dynamometer for grip width. Then, standing erect in a comfortable position, with the dynamometer held first in the dominant hand and then the non-dominant hand for two trials above the point of the vertex, the dynamometer was gripped as forcefully as possible with the arm smoothly moving anterior-inferiorly. The maximum reading was then recorded in kg.f for each participant in the field and in the laboratory testing.

Back strength measurements required participants to sit on the ground with their legs fully extended and the feet pushing against the base of the back strength dynamometer placed against the wall. Participants were required to pull the dynamometer handle as forcefully as possible, using only the back muscles to exert the force (recorded in kg.f). The seated method of measuring back strength was chosen over the upright torso lifting strength test position in order to avoid the possibility of injury to the back musculature for both sets of participants.

Spinal Kinematics – Industrial Lumbar Motion Monitor (iLMM)

The Biodynamics Laboratory at the Ohio State University (OSU) developed the Chattecx^{TM} Lumbar Motion Monitor (LMM), which was designed to identify, monitor and document the vertebral column's three-dimensional motion experienced by the dynamic spine during manual work. The exoskeleton is modelled after the human spine, containing a number of T-sections (20 for the small unit and 26 for the large unit), which are connected via wires, similar to human skeletal vertebrae being connected via ligaments. The work of Marras **et al.** (1992) clarified that the wires lead to four potentiometers at the base of the unit, which change voltage as the wires are twisted and/or stretched, enabling assessment of the trunk during flexion, extension, lateral bending and twisting motions. LMM signals are sampled at 60Hz by the unit and transmitted via an umbilical cable to an analog-to-digital (A/D) converter. Data are then stored on a portable laptop computer for detailed analyses.

Various studies have been conducted to assess the accuracy and reliability of the LMM when measuring changes in position, velocity and acceleration (Marras **et al.**, 1992; Gill and Callaghan, 1996). After extensive testing Gill and Callaghan (1996) concluded that the LMM is suitable for use in clinical and research settings when assessing range of motion (ROM) and changes in velocity. The present study utilised the recently updated industrial Lumbar Motion Monitor (iLMM, BIOMEC®Inc.).

Prior to fitting the iLMM on participants for Tasks 1 or 2, calibration was carried out with the exoskeletal unit lying in the carry case. Following the zero-check calibration the iLMM was secured to the volunteers using the supplied body harnesses; two semi-rigid plates were strapped over the lumbosacral region of the pelvis and around the thorax at the level of the scapulas' inferior angles. Displacement measurements relevant to the human spine were taken in relation to the position of the pelvis using the iLMM. Participants were required to stand motionless in a comfortable stance, so that the unit could be zeroed according to their spinal curvature. Following the zeroing of the iLMM, the task under investigation commenced.

Prediction Models

Ohio State University (OSU) Low Back Disorder (LBD) Risk Model

The Biodynamics Laboratory at the Ohio State University (OSU) developed the LBD risk model (Ballet™2.0, BIOMEC®Inc., 2002). The LBD risk model allows quantitative assessment of working tasks based on the analyses of workplace and trunk motion data. The LBD risk model was used in the present study to quantify the LBD risk associated with each of the laboratory sub-tasks simulating Paintshop and Bodyshop work practices.

3D Static Strength Prediction Programme™ (3D SSPP)

The University of Michigan developed the 3D SSPP (Version 4.3.7, Regents of the University of Michigan, 2004). The strength prediction model is based on and algorithm from the work of Chaffin and Andersson (1984). The inverse kinematics algorithm was developed from research on the preferred postures of individuals manipulating loads with known hand positions (3D SSPP Manual, 2004). The 3D SSPP was used in the present study to assess simulated job design as an evaluation tool pre- versus post-intervention. It should be noted that the developers of the programme suggest that the 3D SSPP should not be used as the sole determinant of worker strength performance or job design based on that performance (3D SSPP Manual, 2004).

Strength and Movement Efficiency – Enraf-Nonius EN-TreeM System

The Enraf-Nonius EN-TreeM system is a Windows-linked stack-weight isoinertial machine which can be used to assess the ROM and strength in testing and rehabilitation settings (Enraf-Nonius B.V., 2004). The EN-TreeM system works on a single or double wire pulley which is connected to a weight stack system. Various movement patterns may be executed by the upper- and lower limbs when using the EN-TreeM system. For the purpose of the present study, the EN-TreeM system was used to provide a standardised load to be moved by the participants in the laboratory during pushing and pulling. The pre-selected load of 20kg.f was selected based on the industrial work observation in the GM plant. An example of the Enraf-Nonius EN-TreeM printout has been included in Appendix D illustrating the average force output (N) recorded for a typical participant in the PTT laboratory simulation. The EN-TreeM software was utilised to ensure that the participant maintained the same effort level consistency (ELC) during the experimentation bout. Post-test analyses allowed for the quantification of average force versus time to ensure ELC in the range of 90 to 110N during the pushing and pulling simulations (highlighted in the example included in Appendix D). Each of the trials was monitored to ensure that participants were not excessively under- or over-taxing themselves during the PTT simulation.

Pushing Action	***Pulling Action***
a *One-handed pushing* 	***b*** *One-handed pulling* 
c *Two-handed pushing* 	***d*** *Two-handed pulling* 
e *Two-handed push intervention* 	***f*** *Two-handed pull intervention* 

Figure 9 a, b, c, d, e and f: *EN-TreeM set-up for pushing and pulling simulation.*
(Task 1: PTT, Conditions A and B)

The EN-TreeM pulley system was set up to restrict the participants to complete the laboratory tasks over the same distances observed for the initial push or pull in the GM Paintshop. The pushing or pulling tasks infrequently require sustained force exertion on the part of the operator, with the present study simulating the initial push or pull to overcome the inertia of the simulated load (representative of the skid).

Participants completed three repetitions for each of the six sub-tasks (with a total of 18 repetitions completed during the session), as shown in Figure 9 a to f. Randomised selection of the pushing or pulling sub-tasks was used at the start of each laboratory testing session.

PHYSIOLOGICAL PARAMETERS

Electromyography - Mega EMG System

The Mega ME3000P Electromyography (EMG) system was used to record muscular activity in the lower back and upper extremity for the PTT (Task 1), and CDC (Task 2). The ME3000P system is a portable, small microcomputer which functions as a collection and recording unit with independent storage capability. The system measures electrical activity by means of recording electrodes applied directly to the skin over superficial muscles. EMG data are registered using state-of-the-art amplification technology in which the amplifier is connected directly to the grounding electrode. This effectively eliminates movement and environmental noise artifacts (MegaWin 2.1 Software Manual, Mega Electronics, Ltd., 2003). Muscle activity is collected by a bipolar configuration and the data may be stored on a SRAM card or can be downloaded to a computer via an interface.

The following protocol was used for recordings completed with the Mega EMG system (following guidelines from the MegaWin 2.1 Software Manual, Mega Electronics, Ltd., 2003):

1) The “belly” of the muscle to be tested was marked (use a measuring tape to obtain the midpoint of the muscle).

2) The skin area was shaved and cleaned (using an alcohol swab) in the area where the electrodes were to be placed.

3) The two electrodes were placed equal distance apart over the midpoint of the muscle.

4) The ground electrode was placed on a bony surface in close proximity and attached to the ME3000P data logger.

Surface electrodes were applied to the muscles used to record EMG activity in the lower back and upper extremity and the specific positions for sensing and ground placements are shown in Figures 10 a to d.

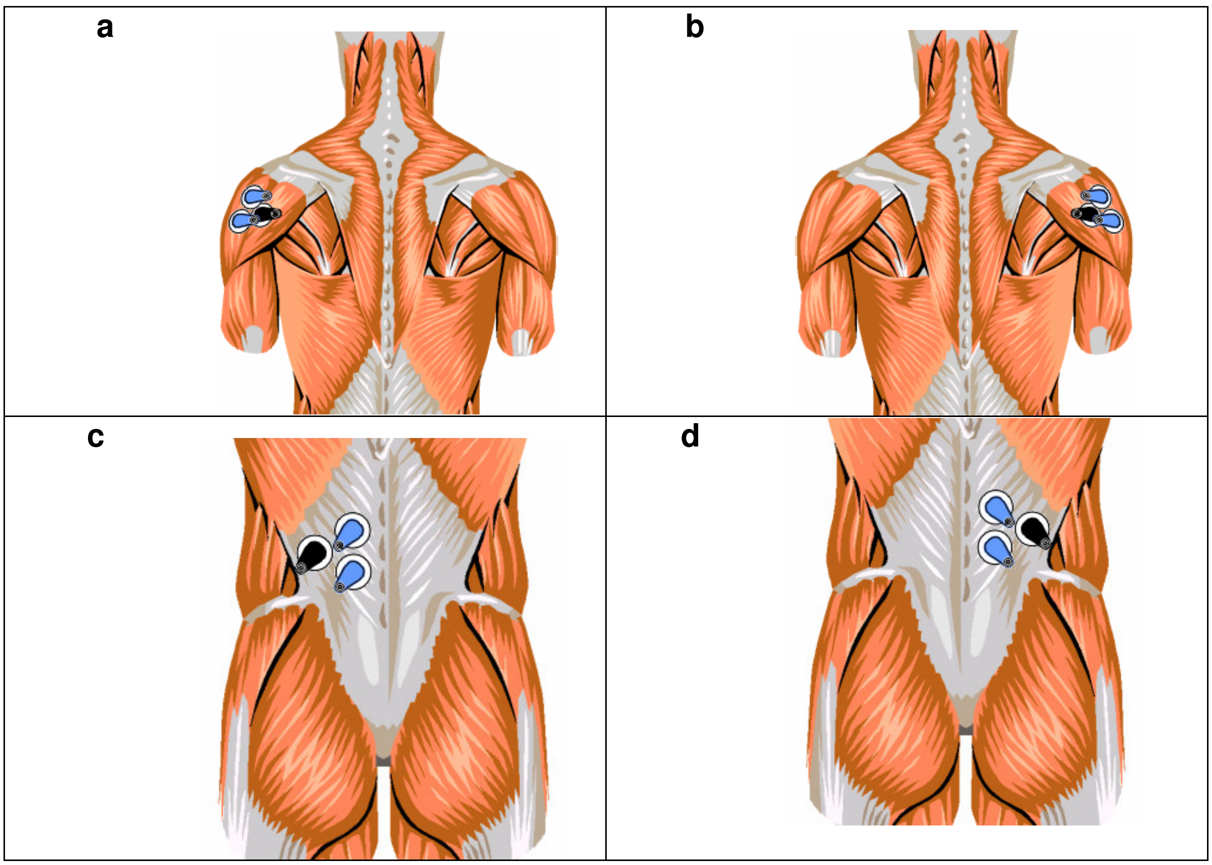


Figure 10 a, b, c and d: *Medial deltoid (a: left and b: right) and erector spinae (c: left and d: right) EMG electrode placement positions used for the PTT (medial deltoid and erector spinae) and CDC (erector spinae) simulations.*
(From MegaWin 2.1 Software Manual, 2003)

EMG muscular activity in the *erector spinae* trunk muscle group has been widely used to predict the muscle activity and biomechanical loading of the lower back (Nielsen **et al.**, 1998; Davis and Marras, 2000), and e*rector spinae* EMG activity was measured for both laboratory tasks (Conditions A and B). The assessment of EMG activity in the deltoid muscles during pushing and pulling has not been extensively researched. In order to add to the understanding of EMG responses while using either one or two hands to complete a pushing or pulling task, the medial heads of the left and right *deltoids* were selected as the focus muscle group during Condition A (PTT). The medial heads of the *deltoids* were selected primarily in an attempt to quantify the decrement in single muscle loading achieved through a change from an asymmetrical to a symmetrical pushing or pulling action, as these one-handed methods of task completion were identified as involving the highest risk to the operator currently working in the GM Paintshop.

Polar™ Heart Rate Monitors: Field and Laboratory Testing

Polar™ Accurex Plus heart rate monitors were used to gain a measure of cardiac strain experienced in both the field and laboratory testing. The Polar™ Coded Transmitter, which measures the heart's electrical activity, was fitted around the participant's chest with a standard heart monitoring strap at the level of the inferior border of the *pectoralis* muscles and in line with the left ventricle situated slightly to the left of the mid-centre of the chest. The Polar™ wristwatch, which acts a receiver, was set to record heart rate responses at 15s intervals during the GM plant field testing sessions and laboratory pilot studies.

Prior to the commencement of the experimentation, a relatively reliable resting heart rate was recorded and used as a 'reference' heart rate, because of the unpredictability of heart rate responses due to anticipation, apprehension, movement, changes in breathing patterns and speech, amongst others. The automotive industry workers were not familiar with heart rate monitoring technology, and a general apprehension of being 'tested' could have distorted resting heart rates. A familiarisation period was therefore arranged during which the experimenter explained the technology to the operators, fitted them with the monitors and then allowed them to complete their normal working cycle while wearing the heart rate monitors for a duration of approximately two hours in the Paintshop or Bodyshop areas.

RT3 Accelerometers: Field Testing

The RT3 tri-axial accelerometer (Stayhealthy Inc., Monrovia, CA) is designed as an activity recording and measurement system for varied research applications. The unit consists of a small reader and was worn on the waist of a subject. It continuously tracks activity through the use of piezo-electric accelerometer technology, which records motion in three dimensions and provides tri-axial vector data in activity units, metabolic equivalent units (METs) or kilocalories (Stayhealthy Inc., 2004). The RT3 units were attached to the belts or clothing of the workers on the posterior side of the body at the waist level (see page 66, Chapter 3). Before the field collection began age, body mass and stature were loaded onto the RT3 unit.

PSYCHOPHYSICAL PARAMETERS

Ratings of Perceived Exertion (RPE): Field and Laboratory Testing

The Ratings of Perceived Exertion scale developed by Borg (1971) is one of the most widely used psychophysical rating scales when assessing the perception of strain experienced by workers or laboratory participants. The scale, which ranges from a value of 6 for basal level of activity to 20 for maximal exertion, was presented and explained in detail to all industrial workers and subjects (Appendix C).

The RPE scale was used in the field to record ratings of Central exertion and Local exertion of the upper and lower extremities. All industrial workers were literate and had a reasonable English vocabulary and were therefore presented with an English version of Borg's scale, which they used to identify their individualised RPE. RPE ratings were taken every 15min during the 2h work observation sessions. Operators were asked to give their RPE ratings for Central exertion followed by ratings of Local exertion.

Laboratory use of the RPE scale was limited to the CDC experimentation due to the short duration of the PTT testing. The CDC Central ratings were recorded every minute for 10min and Local ratings alternated between recordings for the back and arms every alternate even minute (min2, 4, 6, 8 and 10). Participants were required to clearly verbalise responses during the completion of the task and requested not to allow the RPE recording to interfere with the work cycle.

Body Discomfort Map and Rating Scale (BDS): Field and Laboratory Testing

Corlett and Bishop (1976) developed the Body Discomfort Map. Although the original Body Discomfort Map only provides a posterior view of 12 body parts, an adapted version including anterior and posterior views, 27 body parts and a 10-point intensity rating scale ranging from 1 for minimal discomfort to 10 for maximal discomfort was presented to the subjects (see Appendix C). Again, the purpose of the Body Discomfort map and its rating scale was explained in detail to all participants. Body discomfort ratings were recorded after the 1st and 2nd hours *in situ*. Industrial workers were required to rate the area of greatest discomfort and level of intensity. They were then asked to report any additional areas of discomfort and again rate the intensity of that discomfort. Laboratory participants were required to rate the three areas of greatest discomfort following the PTT and CDC tasks.

Body Contribution Map and Rating Scale: Laboratory Testing

The Body Contribution Map and Rating Scale (adapted from Corlett and Bishop, 1976) was used to assess the perceptual responses of participants to the PTT tasks. Participants were asked to rate the areas of the body which they felt contributed the most to each of the specific pushing or pulling actions required for the PTT simulation. For example, during the two-handed pushing task, participants were required to consider the contribution of the upper extremities (and other body regions) during the pushing action. The body contribution map was not used during the field testing in the Paintshop at the GM plant.

LABORATORY TREATMENTS

Laboratory experimentation was conducted in two Ergonomics Laboratories in the Department of Human Kinetics and Ergonomics at Rhodes University. Thirty male volunteers participated in this research project and each subject was required to participate in three sessions.

Session 1: Introduction and Familiarisation

The introductory laboratory session involved explaining the procedures to the student volunteers verbally and in writing. Participants were also afforded sufficient time to raise any queries they might have had relating the experimental protocol. Subjects were then requested to sign an informed consent form before participating in the study. Thereafter basic and anthropometric data were collected, which included age, stature, body mass, acromiale height, stylion height, trochanteric height, back strength, and dominant and non-dominant grip strength. The workplace parameters obtained in the industry were used to set up a similar workstation in the laboratory to simulate the selected task. The familiarisation session aimed to place participants at ease and minimise any responses brought about by pre-experimental anxiety and anticipation, rather than the laboratory treatments. Participants were then familiarised with the simulated Paintshop and Bodyshop work tasks, as well as the testing instrumentation which would be used in both laboratory areas. Due to the work inexperience of the student cohort, a brief video taken during the field observation was shown during the familiarisation session. The video contained footage of the automotive Paintshop and Bodyshop areas showing the two simulated tasks independently. This allowed participants to observe the actual methods used in the workplace and also allowed for clarification of the rationale behind the set-up of a restricted workspace in the laboratory. Digital still photographs were also shown demonstrating the current methods of task completion and highlighting the major problem areas identified during fieldwork. A brief habituation session, which involved fitting the subjects with the Polar™ heart rate monitor and the iLMM harnesses, allowed the subjects to familiarise themselves with the equipment and the tasks they would be required to perform.

Sessions 2 and 3: Experimentation

The experimental sessions (Sessions 2 and 3) required the completion of the two simulated automotive tasks (for both pre- and post-intervention). Randomised testing was used in assigning the volunteers to either the pre- or post-intervention experimental tasks at the commencement of testing.

Task 1: Paintshop Trolley Transfer (PTT) Simulation

The Paintshop pre-intervention simulations (Condition A) required that participants complete simulations for one and two-handed asymmetrical pushing, and one-handed asymmetrical and two-handed symmetrical pulling tasks (with an excessive lean). The load selected of 20kg.f was the same for all testing conditions as this value represented the sustained force output required of the worker during the fieldwork observation. The experimental setup was aimed at simulating the current mean workplace demands (approximately 20kg.f) as closely as possible. Work methods evaluated during the laboratory testing were thus aimed at eliminating unsafe work practices through the provision of guidelines that proposed symmetrical working postures where the operator was working in the position of the greatest strength and lowest likelihood of MSIs and S, T and F accidents. The skid unit could not be installed in the laboratory and this limitation must be considered when recommendations are made based on the push-pull laboratory findings. EMG electrodes were placed in the pre-selected positions (left and right *erector spinae* and left and right *medial deltoid*) and the unit readied for collection. The basic protocol used for both pre- and post-intervention testing is summarised in Table IV.

Table IV: *Task 1 PTT protocol followed for laboratory testing on volunteer male participants. (n = 30)*

Action	Trial	Force Output Required (kg.f)	Number of Repetitions
Pushing	i. One-handed (asymmetrical)	20	3
	ii. Two-handed (asymmetrical)	20	3
	iii. Two-handed Intervention (symmetrical)	20	3
Pulling	i. One-handed (asymmetrical)	20	3
	ii. Two-handed (symmetrical)	20	3
	iii. Two-handed Intervention (symmetrical)	20	3

Each participant was required to complete a total of six trials and 18 repetitions during the laboratory push-pull evaluation. Adequate rest was provided to ensure that the participants were not cumulatively fatigued as a result of the force output required during testing. Figure 11 demonstrates the experimental and EMG electrode set-up for the pushing and pulling assessments. For the purposes of simulating the load the Enraf-Nonius Entree-M weight stack system was used. Heart rate responses were recorded throughout the experiment, whereas LMM and EMG data were obtained at pre-determined stages at min3, 6 and 9 during the trials of the task. Participants were asked to rate their 'Central' and 'Local' RPE on completion of the three trials for pushing or pulling pre- and post-intervention. Participants were shown the Body Discomfort Map and Rating Scale at the end of the laboratory testing session and asked to rate any areas of discomfort experienced.

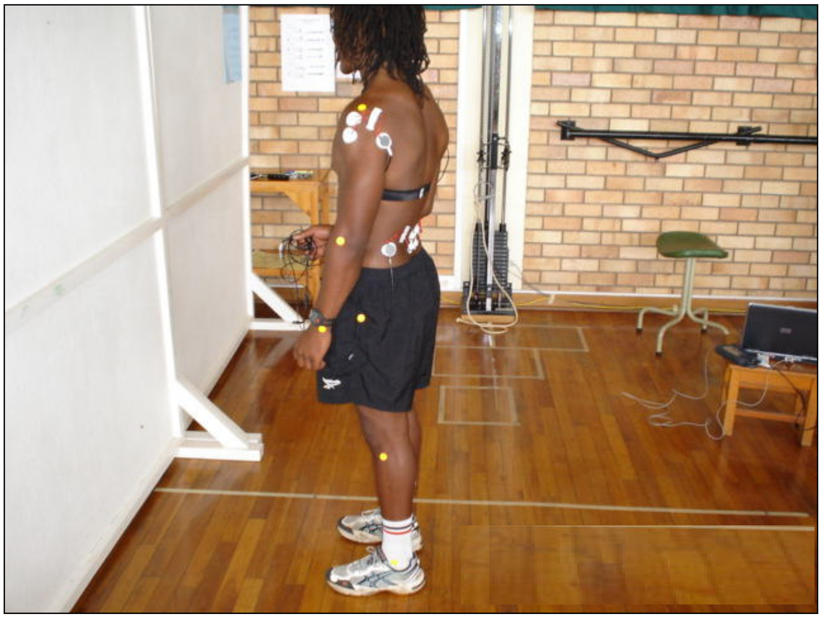


Figure 11: *Participant setup and electrode placement on the medial deltoid (left and right) and erector spinae (left and right). (Task 1: PTT)*

The post-intervention testing was completed utilising the preferred action established in the pilot phase of the present study, namely two-handed pushing and pulling (both symmetrical). Figure 12 illustrates the participant set-up for pulling and pushing post-intervention. The two-handed pulling action places the operator in a symmetrical position, so minimising the likelihood of twisting the spine. A rope pulling system was used as an intervention as per field observation of the operators' "low-cost" method currently in use in the GM plant.

Similarly, two-handed pushing allows the worker to complete a more symmetrical pushing action which does not differentially tax the musculoskeletal system. Mean force requirements for the two-handed push were also shown to be consistently lower in the fieldwork Paintshop force evaluation, with mean values observed ranging from 4.9 to 8.5kg.f depending on the vehicle unit moved.

a

b

Figure 12 a and b: *Participant set-up for the two-handed pull symmetrical intervention and two-handed push symmetrical intervention. (Task 1: PTT, Condition B)*

Task 2: Car Door Carriage (CDC) Bodyshop Simulation

The Bodyshop simulation evaluated the carriage of vehicle doors from an industrial storage bin (both supplied by the GM plant) to a trolley jig constructed in the Department of Human Kinetics and Ergonomics. Manual lifting and carry distances

(H-factors, 900mm; V-factors, 1100mm and carriage, 6.5m) and temporal factors (30s per work cycle) were kept consistent with those observed in the GM plant during the field investigation (see Appendix B for field set-up and task observation sheets).

Prior to the pre- or post-intervention lifting, carrying and placing operation, each subject was fitted with the Polar™ heart rate monitor and a "reference" recording taken. The harness fitting and calibration of the iLMM was completed for each volunteer's natural spinal curvature while they were standing in a relaxed upright posture. EMG electrodes were placed in the pre-selected positions (left and right *erector spinae*) and the unit readied for collection. Once the subject had been re-familiarised with the CDC they completed the required work task for a period of 10 min. Participants were instructed to return to a demarcated lifting area where they lifted the next car door. EMG and iLMM data were recorded for trials at pre-determined times under both testing conditions (min3, 6 and 9). A rest period of at least 20 minutes was required between pre- and post-intervention conditions enabling the participant to recover and to allow the heart rate response to return to reference levels. Table V shows the testing set-up used for the CDC simulation for both the pre- and post-intervention testing protocols.

Table V: *Task 2 CDC protocol followed for laboratory testing on volunteer male participants.*
(n = 30)

CDC Pre-Intervention (Condition A)	**Task Description**
Sub-task i	Step into storage bin, lift door and step out
Sub-task ii	Turn and carry the door past a simulated obstruction in the laboratory
Sub-task iii	Turn and place the door on the simulated jig
CDC Post-Intervention (Condition B)	**Task Description**
Sub-task i	Step into storage bin, lift door and step out
Sub-task ii	Turn and place the door on transfer trolley and push along "line"
Sub-task iii	Turn and place the door on the simulated jig

The research design, which utilised a pre-test / post-test set-up, allowed for the evaluation of the effectiveness of the proposed ergonomics interventions before implementation in the automotive assembly plant. Laboratory-based findings were discussed with the operators and GM management to develop interventions most suitable to the Struandale plant. These adapted interventions were then presented to GM Plant Engineering and Safety, Health and Environment (SHE) management together with the results of the laboratory experimentation. Once the interventions had been put into practice and the workers had enough time to get accustomed to the changes, a re-evaluation of the operators' physical and psychophysical responses to the Paintshop and Bodyshop tasks were conducted after a period of six months.

STATISTICAL ANALYSIS

Experimental data were transferred to the STATISTICA (Version 7.0, StatSoft®) statistical software package. Basic descriptive statistical analyses were completed on all relevant variables, providing general information regarding the sample's responses (see Appendix D for example).

The statistical matrix for each of the two independent tasks is set out in the sections that follow. Task 1 (PTT) included six sub-tasks (three pushing and three pulling) which were divided into pre- and post-intervention conditions (A and B). Task 2 (CDC) included three sub-tasks divided into pre- and post-intervention conditions (A and B). Statistical analyses (t-tests and ANOVA, $p \leq 0.05$) were carried out for each of the three statistical hypotheses presented in Chapter One (see p7).

Task 1: PTT Statistical Analyses

Spinal kinematics (Hypothesis 1), physiological responses (Hypothesis 2) and psychophysical ratings responses (Hypothesis 3) were compared pre- and post-intervention by means of related t-tests and one-way ANOVA (where appropriate).

Pushing

Pre-Intervention (Condition A)	i. One-handed Pushing	ii. Two-handed Pushing
Post-Intervention (Condition B)	iii. Two-handed Pushing Intervention	

Pulling

Pre-Intervention (Condition A)	i. One-handed Pulling	ii. Two-handed Pulling
Post-Intervention (Condition B)	iii. Two-handed Pulling Intervention	

Task 2: CDC Statistical Analyses

Spinal kinematics (Hypothesis 1), physiological responses (Hypothesis 2) and psychophysical ratings (Hypothesis 3) were compared pre- and post-intervention by means of related t-tests.

CDC

Pre-Intervention (Condition A)	i. Lift	ii. Carry	iii. Place
Post-Intervention (Condition B)	i. Lift	ii. Trolley Push	iii. Place

CHAPTER FOUR
FIELD FINDINGS, EXPERIMENTAL RESULTS AND DISCUSSION

INTRODUCTION

Automotive assembly plants frequently necessitate taxing physical labour during the completion of basic manufacturing tasks. In order to assess the current task demands placed on the operator, visits to a cross-section of original equipment manufacturers were completed. Work-related hazards currently affecting the overall efficiency of the human operator working in the automotive sector were identified and quantified using varied methods, including video, digital photographic analyses, physiological monitoring and perceptual rating scales. Specific laboratory simulations of selected tasks were completed following the *in situ* investigation, and detailed laboratory assessments allowed for the effective quantification of task demands, taking into consideration the biophysical, physiological and perceptual responses of the operator, and the effectiveness of intervention strategies.

The General Motors (Struandale) plant was selected as the focus operation for the field observation and follow-up study. Detailed field assessments were completed prior to the laboratory testing sessions, which served to familiarise the researcher with the general set-up of operations. Renz and Scott (2004) suggested that while most manual tasks display a combination of potential problem factors which need to be considered in conjunction with their environmental and organisational context, interventions may have to be restricted to combating the most severe factors. Wide-ranging factors influencing workplace variability were directly considered during the field observation in both the Paintshop and Bodyshop at the GM plant, for as Allread **et al.** (2000) reported, variability in work completion depends upon experience, physical differences between operators or individual preferences for how the work is performed.

FIELD OBSERVATIONS

Field Task 1: Paintshop Area

Recent research has suggested that pushing and pulling actions are common in a range of workplaces (Kumar, 1995; van der Beek **et al.**, 1999) and similarly the GM Paintshop exhibits a high prevalence of push-pull sub-tasks with heavy vehicle frames manually moved on skid platforms during the course of the work cycle. Workers are required to complete one and two-handed pushing or pulling to move the units on transfer trolleys in this area of the plant (see Figure 4, p57). Field observations focused on a number of key areas, including recording of workspace dimensions, current task requirements, plus the workers' anthropometric characteristics, physiological and perceptual responses. Basic task observation sheets were used to assess the current workflow and divide the job into a series of sub-tasks (see Appendix B for an example from the Paintshop). Operators in this area were required to work on various models of car frames, with the heaviest ("worst-case") selected for evaluation in the laboratory.

Field Task 2: Bodyshop (Closure Line) Area

The automotive Bodyshop is an area that is characterised by high noise and temperature levels (particularly in the hot summer months in South Africa) due to the welding operations that take place in this confined area. A large amount of manual work is still completed on the Bodyshop Closure Lines of the GM plant. The manual activities include the carriage of car doors, boot lids and bonnets, which are all heavy and awkward to manoeuvre. The laboratory simulation for the Bodyshop Closure Line tasks was aimed at identifying the current demands placed on the operators as a result of the manual handling of the door, and then evaluating the proposed ergonomics intervention strategies developed to decrease the current workload.

Workplace Environmental Factors

It is well documented that the environmental conditions experienced in the workplace will have a distinct impact on the physical and cognitive responses of the operator, and

Snook and Ciriello (1974) reported that operator ability to complete manual work declines significantly when temperatures increase up to and beyond 27℃. Table VI shows that it was not uncommon to have temperatures in the region of 27℃ in the GM plant, and in mid-summer they often exceed 30℃. The mean noise levels in both focus areas exceeded the 85 dB(A) limit set by the South African Occupational Health and Safety Act (OHS Act, 1993). In accordance with the OHS Act (1993), clear demarcations of noise zones were evident in the relevant areas of the plant. However, despite the availability and provision of adequate personal protective equipment (PPE) in the form of hearing protection, PPE usage was not uniformly enforced, particularly in the Bodyshop.

Table VI: *Workplace ambient temperature and noise levels in the Paintshop and Bodyshop areas of the GM plant.*

Plant Area:	Time of Day:		
Paintshop	***10.30***	***11.30***	***12.30****
Ambient Temperature (℃)	26.5	27.3	28.6
Noise Level (dB(A))	85.8	86.7	85.8
Bodyshop Closure Line	***12.30***	***13.30***	***14.30****
Ambient Temperature (℃)	26.1	27.1	26.3
Noise Level (dB(A))	92.6	96.1	89.2

* *Working cycle times vary due to varied rest breaks in the Paintshop and Bodyshop areas; hence a time overlap was not possible*

Observations of Selected Tasks

Time-motion observations were conducted to assess the current work demands in the two areas evaluated. Priority areas and associated high risk sub-tasks were identified based on the observation. The Paintshop Trolley Transfer (PTT) push-pull, and the Bodyshop Car Door Carriage (CDC) were identified as the highest risk tasks requiring prioritisation of ergonomics intervention. Laboratory interventions were subsequently developed in an attempt to minimise the workplace risk to the automotive workers.

The Paintshop sub-tasks identified were subdivided into five main categories as follows: one-handed push, two-handed push, one-handed pull, two-handed pull and pulling the skid to a stop (shift time 7.5h). Each of these sub-tasks was then observed and an average work cycle time for the complete transfer of the vehicle frame of 50s was recorded for the six operators working in this area. The most prevalent actions were the one-handed push and pull operations. All operators made use of these methods during the shift, whereas certain operators were not required to pull the skid to a stop or use a two-handed push or pull action. The estimated time for each of the five sub-tasks ranged from 3 to 15s, depending on the distance of push or pull along the Paintshop line. The longest one-handed pulling effort was recorded as 15s where the operator moved the skid along the line and then pulled it further along the track transfer line.

The Bodyshop sub-tasks identified included lifting, carrying and placing of the car door onto the jig on the Closure Line (shift time 7.5h). The mean work cycle time in this area was 29s with a range of 25 to 42s observed on the line. The mean time required for the lifting of the door from the bin was 15s, while carrying the door required approximately 12s, and finally the placement of the door took 2 to 3s to ensure that the door was correctly placed on the jig. The temporal recordings from the field were subsequently used to establish a laboratory test cycle of 30s.

FIELD BIOPHYSICAL PARAMETERS

Paintshop Push-Pull Force Evaluation

It was evident that pushing and pulling tasks were prevalent in the automotive plant, particularly in the Paintshop area. In order to quantify the current task demands placed on workers, isometric pushing and pulling forces were measured using the Chatillon™ hand-held dynamometer during testing at the GM plant. Repeated measures were collected for three vehicle models and the effort level consistency requirement set in the 93 to 107% range (see Table VII). Effort level consistency was calculated following Charteris and James (2000) using the following formula: ***ELC % = (Trial X/Trial Y) x 100.***

Table VII: *Pushing and pulling forces measured in the Paintshop of the GM plant.*

Pulling Forces	***Trial 1***		***Trial 2***		***Trial 3***		***Effort Level Consistency (ELC%) ****		
Model A	***Mean***	***Peak***	***Mean***	***Peak***	***Mean***	***Peak***	***T1 vs. T2***	***T2 vs. T3***	***T1 vs. T3***
One-handed	8.2	16.7	9.5	21.1	8.0	19.7	86.32	118.75	**102.50**
Two-handed	11.1	17.2	8.5	17.0	8.6	18.8	130.59	**98.84**	129.07
Model B									
One-handed	6.1	16.6	4.8	10.8	4.8	12.0	127.08	**100.00**	127.08
Two-handed	8.8	15.0	7.1	18.1	6.8	16.3	123.94	**104.41**	129.41
Model C									
One-handed	12.1	21.0	10.5	18.2	12.3	21.7	115.24	85.37	**98.37**
Two-handed	13.6	20.1	14.0	23.6	12.7	21.2	**97.14**	110.23	107.08
Pushing Forces									
Model A	***Mean***	***Peak***	***Mean***	***Peak***	***Mean***	***Peak***	***T1 vs. T2***	***T2 vs. T3***	***T1 vs. T3***
Two-handed	5.0	15.7	4.4	12.5	5.3	15.2	113.64	83.02	**94.34**
One-handed	5.6	11.0	4.8	10.6	5.3	8.8	116.67	90.57	**105.66**
Model B									
One-handed	6.3	10.4	7.6	12.0	6.3	12.3	82.89	120.63	**100.00**
Two-handed	5.4	13.8	4.7	14.6	5.0	16.3	114.89	**94.00**	108.00
Model C									
One-handed	9.9	20.5	10.3	21.7	10.8	22.0	**96.12**	95.37	91.67
Two-handed	7.0	17.9	7.5	19.7	11.1	22.3	**93.33**	67.57	63.06

* *Effort Level Consistency (ELC) based on Charteris and James (2000).*

Note: *Figures in bold indicate the highest ELC recorded during the field investigation. ELC was set in the range from 93-107% during the force evaluations.*

The Paintshop personnel supplied the masses and dimensions of all vehicle units evaluated in the field. The current worst-case scenario, vehicle Model C (600kg) was shown to be considerably heavier than the two other units. Force output requirements were subsequently highest for moving this unit on the skid. Peak initial forces required to move the skid ranged from 18.2 to 21.7kg.f for the one-handed pull, and values for the two-handed pull ranged from 20.1 to 23.6kg.f. A similar range of values were recorded for the pushing tasks. The one-handed push range was 20.5 to 22.0kg.f and the two-handed push range from 17.9 to 22.3kg.f for vehicle Model C.

Certain one- and two-handed push-pull tasks were consequently selected for detailed laboratory investigation. Based on the findings of the field hand-held dynamometry force evaluation, the laboratory simulations of pushing and pulling were standardised at 20kg efforts for the six simulation trials. The 20kg output requirement was deemed to be representative of the current task demands; however, it is important to note that the skid unit does not always move smoothly on the roller system and is dependent on the state of the wheels of the skid and the tracks in the Paintshop. There are instances where much higher forces may be required to overcome the moment of inertia requirements of the sub-task under investigation, as James and Todd (2003) found that values may well exceed 40kg.f if the operator was required to bring the skid unit to a stop once it has started to move. Previous research conducted by James and Todd (2003; 2004) demonstrated that push-pull tasks were identified as posing a high-level of risk to the operator. In a number of field observations conducted on experienced operators the force requirements may tax them to a level equivalent to 95% of their maximal strength potential (James and Todd, 2003).

Working Postures in the Paintshop

The GM Paintshop had a predominance of pulling and/or pushing heavy and awkwardly shaped vehicle frames on a frequent basis during the work shift. The high forces required in many of these pull and push tasks necessitated that the operators adopt working postures which resulted in the centre of mass (CM) being located at the extreme limits of their base of support (BS). It is well known that the height of the CM from the ground will influence stability (Haslam **et al.**, 2002; James and Todd, 2003), and due to the height of the vehicle units from the factory floor, workers were unable to adopt a working posture that was likely to ensure optimal stability.

A combination of the working posture, floor surface and load requirements resulted in the workers not only being unable to exert maximal force, but also substantially increased instability and the likelihood of slipping or tripping in the workplace (James and Todd, 2003; Todd **et al.**, 2004). The awkward posture demonstrated in Figure 13 further exposed the workers to higher levels of discomfort and the likelihood of cumulative WMSDs. In investigating potential intervention strategies based on Paintshop operations, one-handed pulling was identified as a major concern, while two-handed symmetrical pushing was identified as providing the most suitable working posture for production of the required force to move the skid unit.

Figure 13: *Working posture showing pulling with centre of mass (CM) outside the base of support (BS) in the Paintshop at the GM Plant.*

Working Postures in the Bodyshop (Closure Line)

Due to restricted space and the placement of storage bins close to the welding line, the doors are lifted from a raised bin (Figure 14a) and then carried to the side (Figure 14b). The analyses of Bodyshop working postures demonstrated that the current task demands place the operator in a twisted position with the door carried at shoulder height or above when carrying the door from the bin to the jig for final placement.

a **b**

Figure 14 a and b: *Working posture showing lifting position (a) and carriage (b) of the door in the restrictive Bodyshop Closure Line.*

Basic intervention strategies were sought which allowed the worker to minimise the step into the storage bin and the amount of time spent in a twisted and asymmetrical posture while carrying the door, as these factors were identified as involving the greatest risk to the worker. Workers completing the lift, carry and placement of the car door worked on one side of the Closure Line for the entire shift (either right or left sided carrying). The working posture during the door carriage therefore differentially taxes the musculoskeletal system of the operators working in the Bodyshop.

FIELD PHYSIOLOGICAL VARIABLES

Heart Rate Responses

Workplace MMH task requirements place physical stresses on the operator, which strain the cardiovascular system (Dempsey, 1998; Kumar, 2001). Mean heart rate values recorded during the fieldwork observation were 93.5 (±9.77) $bt.min^{-1}$ for the Paintshop, and 89.7 (±13.98) $bt.min^{-1}$ for the Bodyshop workers. Figure 15 demonstrates that mean heart rate responses were higher in the Paintshop in five of the sampling periods, but the highest heart rate was recorded in the Bodyshop area, with a range from 80 to 115 $bt.min^{-1}$ in the Paintshop, and between 70 and 124 $bt.min^{-1}$ in the Bodyshop area.

Unrelated t-Tests revealed a significant difference ($p \leq 0.05$) between the Paintshop and Bodyshop operators' 'working' heart rate responses during minute 75 (the first collection period of the second hour). This atypically lower mean heart rate response may be explained by considering the rest schedule used in the Bodyshop Closure Line. During selected periods of the shift, workers are permitted to take unscheduled rest breaks (usually taken after approximately 60min), and the result was a significantly lower mean heart rate for the Bodyshop workers. No other statistically significant differences were observed between Paintshop and Bodyshop heart rate recordings.

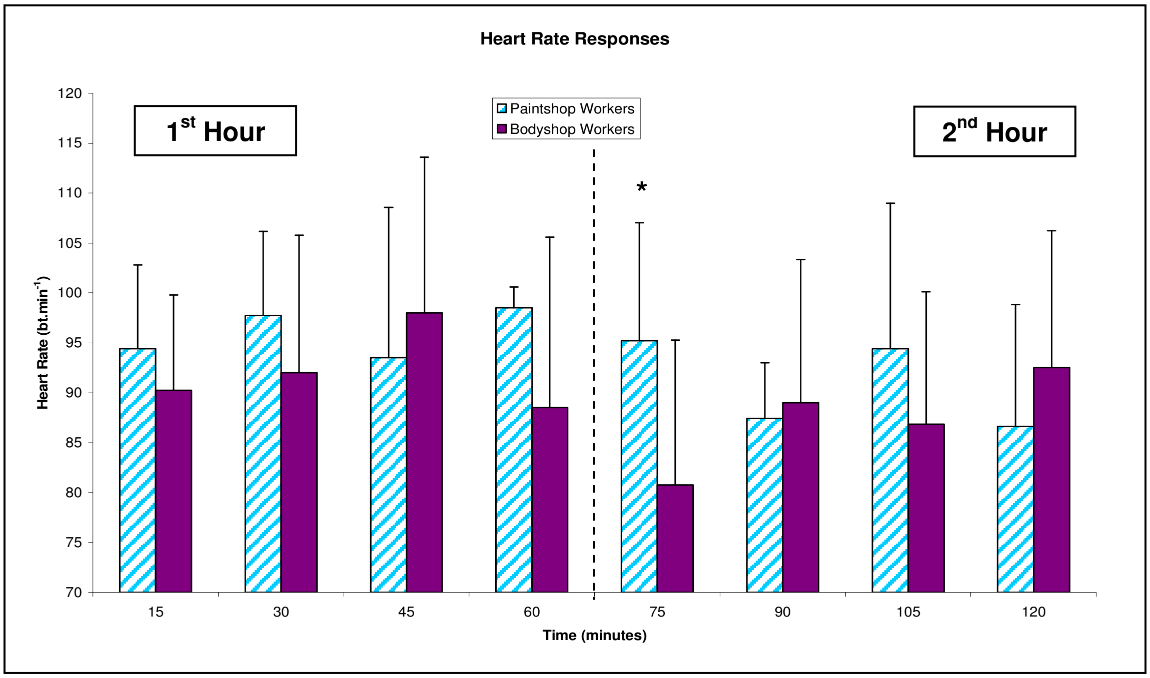


Figure 15: *Heart rate responses recorded in the GM Struandale Paintshop and Bodyshop Areas.*
(n=6 in Bodyshop and n=6 in Paintshop)

** denotes significant difference ($p \leq 0.05$) between Paintshop and Bodyshop responses.*

According to accepted guidelines established by Sanders and McCormick (1993), both sets of heart rate responses would suggest that the current tasks did not place excessive demands on the cardiovascular system when using heart rate responses as a guideline. Research has suggested that the maintenance of acceptable physiological output, as observed in the Paintshop and Bodyshop areas, should reduce the onset of worker fatigue or extreme discomfort over the working shift (Datta **et al.**, 1983; Renz and Scott, 2004). However, it is argued that low-cost interventions will further reduce the physiological strain placed on the operator in the automotive plant.

Activity Count: RT3 Accelerometers

The RT3 tri-axial accelerometer (Stayhealthy Inc., Monrovia, CA) is designed as an activity recording and measurement system for varied research applications. The RT3 units were attached to the belts or clothing of the workers on the posterior side of the body at the waist level. Calculated activity calories were converted to kilojoules per minute using the method described in Chapter 3 (see page 66).

Table VIII: *Derived energy expenditure predictions from RT3 Accelerometer data collected in the GM Paintshop and Bodyshop areas.*

Area	kJ.min^{-1}	kJ.h	kJ.shift
Paintshop	12.3 (1.60) *	736.5 (95.97) *	5 523.7 (719.81) *
Bodyshop	10.7 (1.34)	642.9 (80.24)	4 822.0 (601.81)

(Means with standard deviations in brackets)

* *denotes significant difference ($p \leq 0.05$) between Paintshop and Bodyshop responses.*

The energy expenditure predictions calculated in the Paintshop showed a significantly higher metabolic cost ($p \leq 0.05$) over a minute, hour and the full shift compared to Bodyshop values. These findings are reflective of the different work rate of the two jobs. The activity levels in the Bodyshop area are in large part self-paced, and additionally the line is occasionally subject to production slow downs and unit backlogs. The operators in the Bodyshop are thus afforded more informal rest breaks than is the case for the operators working the Paintshop, particularly at the track transfer line.

FIELD PSYCHOPHYSICAL RESPONSES

Ratings of Perceived Exertion (RPE)

Ratings of Perceived Exertion (RPE) provide a useful perceptual indication of operator perceptions of current working demands. Central ratings were recorded to gain an understanding of the perceived demands placed on the cardiovascular system while carrying out the Paintshop and Bodyshop sub-tasks. Care was taken to ensure that workers were familiar with the purpose of the scale and ratings were clearly specified for Central and Local exertion.

Significant differences were observed during minutes 15, 75, 90 and 105 for Central RPE ratings for industry workers. It is worthwhile noting from Figure 16 that the perceptions of exertion are higher for Bodyshop workers after the first 45min, indicating that despite recording lower mean working heart rates in the Bodyshop, the manual labour requirements were perceived to be more demanding while carrying car doors in the Bodyshop than is the case for completing the Paintshop trolley push-pull tasks.

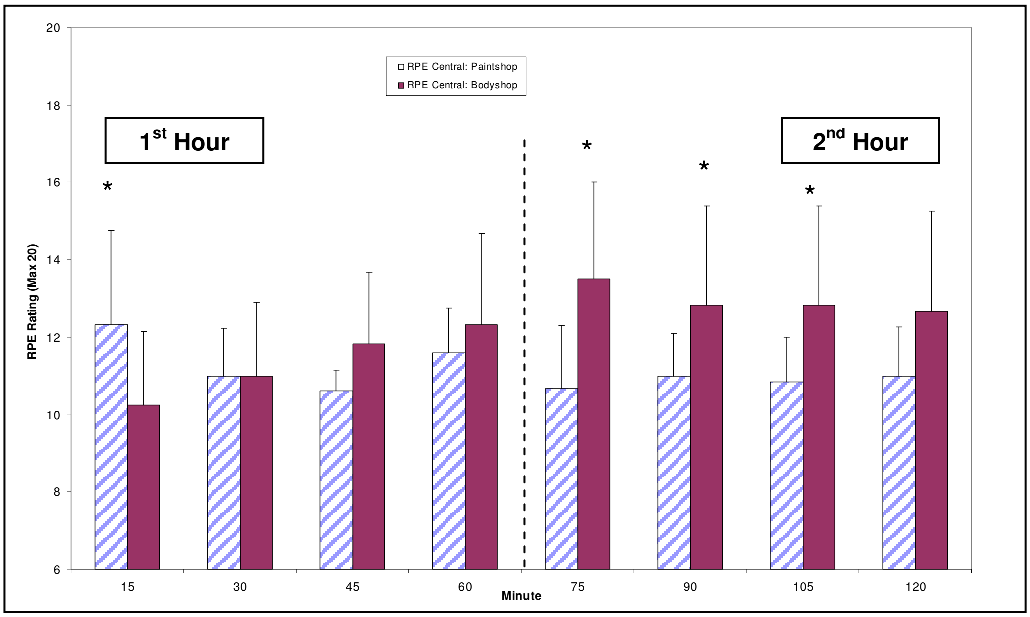


Figure 16: *Central RPE ratings for Paintshop and Bodyshop workers in the GM plant.*
(n=6 in Bodyshop and n=6 in Paintshop)

**denotes significant difference (p ≤ 0.05) between Paintshop and Bodyshop responses.*

Paintshop RPE ratings did not alter much over the two hours, indicating that workers maintained a comfortable working pace and did not perceive the task demands to be unduly excessive. Job familiarity may be a possible reason for this finding, as the workers in the Paintshop had longer mean work experience (7yr) than the Bodyshop workers assessed.

It is well accepted that the perception of exertion has an important application in any occupational setting, particularly during the evaluation of physically demanding tasks, and Figure 17 shows the responses for RPE specific to Local exertion (focusing on the back and arms) during the field observation. Responses in the Bodyshop show an expected trend, with ratings increasing steadily from min 15 to min 60 of observation as the operators become more fatigued due to the accumulative effect of carrying an awkward shaped door. Workers on the Closure Line had just been given the opportunity to rest and RPE responses were subsequently lower than those in the Paintshop by the end of min 75. In contrast, Local RPE scores show a steady increase up to min 60 and then tend to stabilise during the second hour of collection.

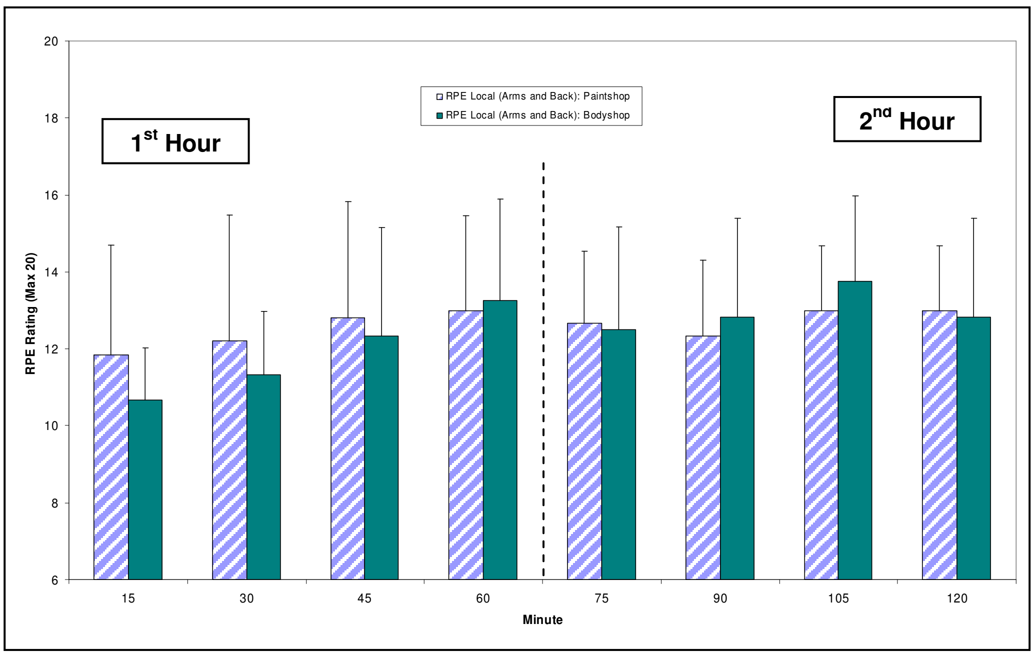


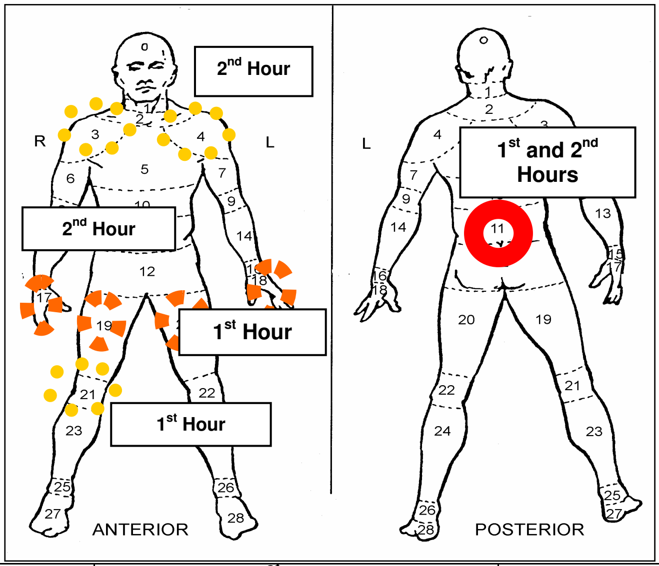
Figure 17: *Local RPE ratings for Paintshop and Bodyshop Workers in the GM plant.*
(n=6 in Bodyshop and n=6 in Paintshop)

Statistical analyses of localised ratings revealed no statistically significant differences between Paintshop and Bodyshop perceived exertion ($p \leq 0.05$). Paintshop operators reported a higher level of perceived exertion than Bodyshop workers in five of the collection periods. Workers in this area reported greater upper extremity exertion due to the pushing and pulling of heavy vehicle frames. In the latter periods of the work shift (min 90 and min 105) Bodyshop workers rated exertion higher for the back region due to the asymmetrical carriage. Local ratings of perceived exertion were generally higher than Central ratings, indicating greater muscular stress than cardiovascular strain in both areas of the GM plant.

Body Discomfort Map and Rating Scale (BDS)

The BDS is a subjective tool used to assess the discomfort of an individual in the laboratory or working environment, and reports of high levels of discomfort experienced during the shift are often an indicator of higher levels of risk in the workplace. The body discomfort ratings shown in Figure 18 indicate that the major area of perceived body discomfort was 11 posterior (the lower back region). Greatest body discomfort was reported in this region by 6 of 12 operators during both the first and second hours. The mean intensity of discomfort experience in this area was 5.5 (± 1.93) on the 10-point rating scale during the first hour, and went up nominally to 5.8 (± 1.71) during the second hour.

Other areas where discomfort was experienced were the biceps (6 and 7 anterior), shoulders (3 and 4 posterior) and thigh regions (19 and 20 anterior) for the Paintshop sub-tasks, due to the push-pull tasks that require substantial effort from the upper extremities to overcome the inertia of the vehicle unit. A few of the workers also experienced discomfort in the lower extremities due largely to the current design of the transfer trolley. The trolley is pulled towards the operator and requires careful maintenance of balance to prevent serious injury in the event of the trolley running out of control. The lower extremities are frequently used to stop the load once the unit is in motion, which results in potential limb injury.



Key	Rating	*1st Hour Area*	*2nd Hour Area*
	Greatest Discomfort: Paintshop and Bodyshop	***11 Posterior Lower Back*** (Mean Rating: 5.5 ± 1.93)	***11 Posterior Lower Back*** (Mean Rating: 5.8 ± 1.78)
	2nd area: Paintshop	***19 and 20 Anterior Right and Left Quadriceps***	***17 and 18 Anterior Right and Left Hands***
	2nd area: Bodyshop	***21 and 22 Anterior Right and Left Knees***	***4 Anterior Left Shoulder***

Figure 18: *Body discomfort experienced at the end of the 1st and 2nd hours during field observation in the GM plant.*

The carriage of the car door requires manual handling, predominantly using the strength output of the upper extremities. However, the lower extremities were also taxed due to the requirement of walking with the load before placement on the jig for spot-welding. The strain experienced by the workers is reflected in the ratings in the Bodyshop, which demonstrated that discomfort was experienced in the knees (21 and 22 anterior), the shoulders (3 and 4 posterior) and the gluteal region (12 posterior). Statistically significant differences in body discomfort were recorded during the second hour of field observation. Paintshop workers rated discomfort levels significantly higher than Bodyshop colleagues. This finding may be explained by considering that task demands, quantified by heart rate, EE values and Local RPE, were higher for the pushing and pulling of the vehicle frames than for car door carriage.

PILOT TEST FINDINGS

Preceding the laboratory experimentation phase, preliminary and pilot studies, based on the initial field evaluations in the GM plant, were conducted in the Ergonomics Laboratories of the Department of Human Kinetics and Ergonomics at Rhodes University. Four male volunteers participated in the pilot testing.

Temporal, Dimensional and Working Posture Analyses

The temporal, dimensional and working postures required for the pilot testing were assessed, and the starting positions adjusted according to the factors observed in the GM plant. The PTT simulation pilot session highlighted the importance of standardisation of the starting foot position in the dynamic push-pull evaluation. Clear foot positioning demarcations were placed on the laboratory floor, as shown in Figure 19, and a familiarisation session was conducted to enable participants to move with as natural a gait pattern as possible while pushing or pulling the simulated load.

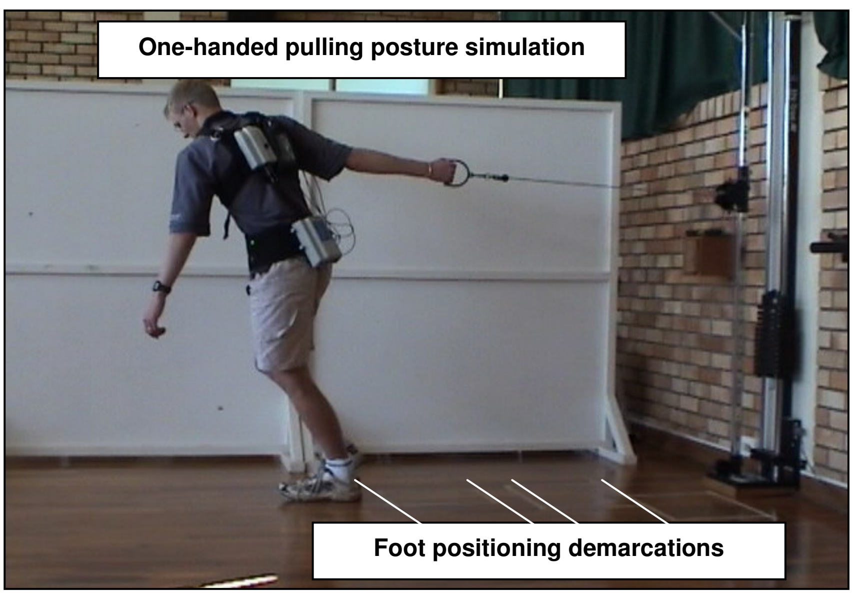


Figure 19: *Pilot testing of the one-handed pulling simulation in the laboratory with the clear starting demarcations.*

The simulated sub-task which placed the greatest restriction on mobility was the two-handed push due to the experimental set-up, and the distance of the push was subsequently shortened from the originally proposed 3m to 1.5m to more accurately simulate the pushing action at the front of the skid unit.

The CDC laboratory simulation required a temporal adjustment during the trolley pushing phase (post-intervention) to allow for comparisons to be made between pre- and post-intervention methods. Initially both the front and rear doors were used; however, after extensive pilot work, it was decided that participants would only be required to lift the front door (mass of 21kg) in order to standardise the task according to the *in situ* work cycle time recorded (30s).

With the introduction of the door trolley the participants were required to place the door onto the trolley, push the trolley the required 6.5m, and then lift the door off the unit to place the door on the jig. While the need to carry the door had been eliminated, the door did need to be placed on, and lifted off, the trolley and this resulted in increasing the pace during the post-intervention phase in the laboratory in order to meet the field work cycle time.

Biophysical and Physiological Parameters

Pilot testing served to modify the work pattern so as to synchronise the collection of experimental data from the industrial Lumbar Motion Monitor (iLMM) with input from the Mega ME3000P electromyography (EMG) system. The PTT testing sessions allowed for real-time sampling using the EMG system as the use of the 'hard wired' method, where the EMG recording unit is plugged directly into the computer for synchronized data collection, was shown to be feasible. In contrast, the CDC tasks required the use of the Mega EMG data logging system due to equipment restrictions. EMG data were later downloaded and assessed using the Mega software package. Consequently, recordings of iLMM and EMG data were limited to minutes 3, 6 and 9 for the purposes of comparison of kinematic and muscular loading during the CDC pre- and post-testing.

Pilot heart rate recordings (mean 109.5 ±0.71 bt.min^{-1}) indicated that no responses exceeded those observed during the field investigation in the Paintshop and Bodyshop areas. The simulated physiological demands were therefore deemed to be acceptable for the laboratory experimentation phase. The pulling and pushing load of 20kg.f was also evaluated during pilot testing. All participants indicated that the load was acceptable for all six sub-tasks and the simulated trolley loading was thus deemed to be acceptable for use during the laboratory experimental phase of the present study.

LABORATORY RESEARCH RESULTS

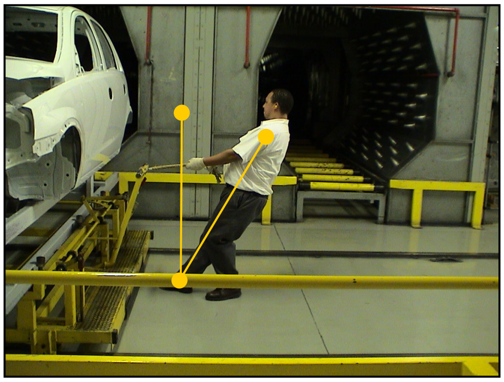
Laboratory experimentation on the selected industrial working operations included two experimental conditions for the push-pull of the vehicle frame (Task 1), and car door carriage (Task 2): simulations conducted included the existing industrial scenario pre-intervention (Condition A), and the post-intervention (Condition B) evaluation conducted to assess the effect of the ergonomics intervention proposed.

TASK 1: PAINTSHOP TROLLEY TRANSFER (PTT) SIMULATION

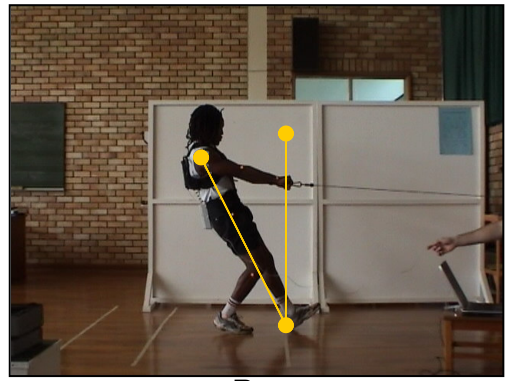
BIOPHYSICAL PARAMETERS

Working Posture Analyses

The one- and two-handed push-pull tasks required participants to adopt awkward working postures pre-intervention, which were sub-optimal for various reasons. Figure 20a to d demonstrates how the pulling tasks differentially physically tax the musculoskeletal system depending on the method of sub-task completion. Figure 20a shows the working posture observed in the GM Paintshop during pulling with two hands. Selected examples of the two-handed pull simulation pre-intervention are shown in Figure 20b and c, with participants leaning excessively as per the workplace observation, and in contrast the post-intervention two-handed pull (Figure 20d) illustrates a more balanced and controlled working posture.



a



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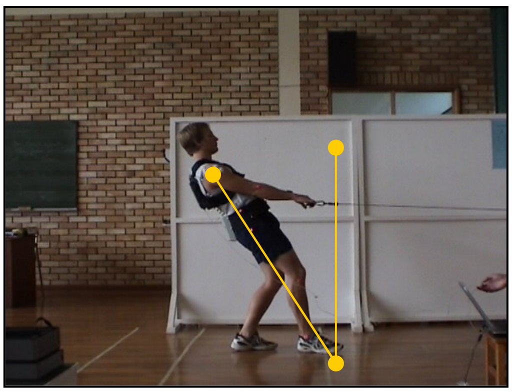

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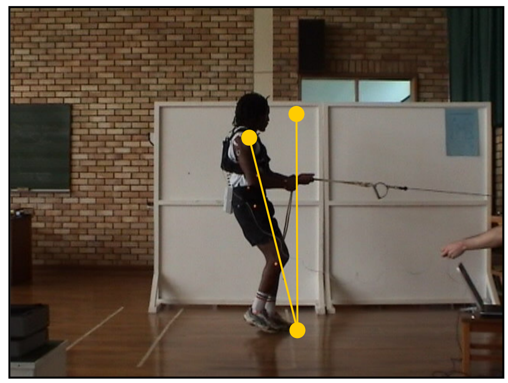


D

Figure 20 a,b,c and d: *Pulling working postures observed in the workplace (a), and simulated during laboratory experimentation (b-d).*

Note: yellow line illustrates the angle of lean from the vertical.

Figure 20a, b and c demonstrates that current working postures increases the risk of trips and falls, particularly when the floor is uneven as is the case on site and, in the longer term, WMSDs.

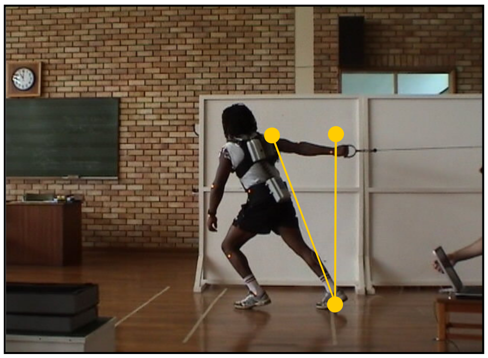
The mean lean angles recorded during two-handed pulling are shown in Table IX, where an angle of 23.7° (±3.51) was recorded for two-handed pre-intervention pulling, which was significantly reduced post-intervention to 13.9° (±2.21).

Table IX: *Mean lean angles recorded from the vertical for two-handed pulling pre- and post-intervention.*

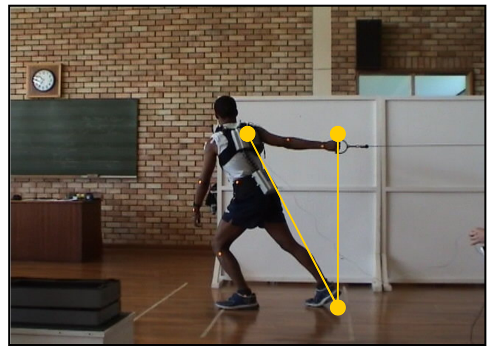
Pulling	Lean Angle	Range
Pre-Intervention	23.7 (3.51)	18.5 to 30.5
Post-Intervention	13.9 (2.21)	9.7 to 16.9

(Means with standard deviations in brackets, shaded area post-intervention)

Pulling using one hand excessively loads the shoulder, elbow and wrist joints of the dominant upper limb. Figure 21a and b illustrates the sub-optimal postures required to move the load in the laboratory, and it is evident that the dominant shoulder joint is particularly taxed. The working posture adopted will also significantly influence the spinal kinematics and physiological responses of the participant, as will be demonstrated in later sections.



a



b

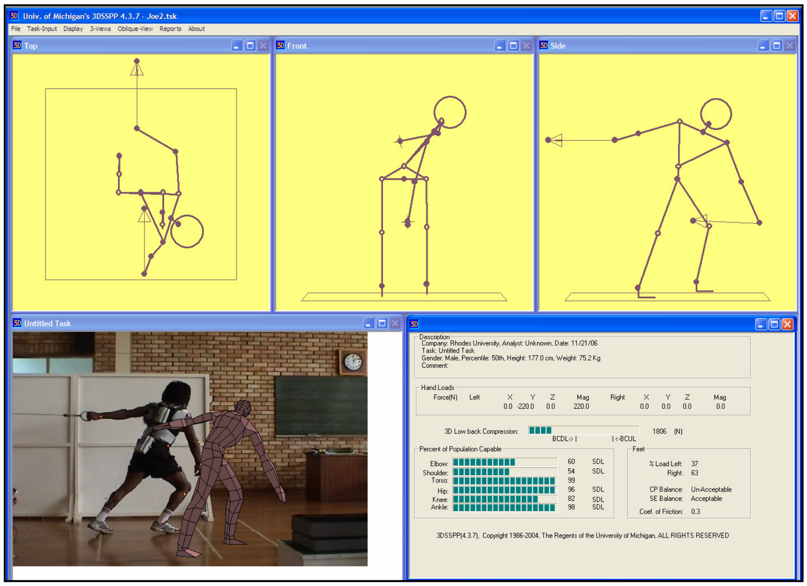
Figure 21 a and b: *Typical one-handed pulling working postures observed during laboratory experimentation.*

Note: yellow line illustrates the angle of asymmetry from the vertical.

The one-handed pulling action placed the right arm in abduction and the mean angle of asymmetry (taken from the vertical to the right acromial process as shown in Figure 21a and b) was 25.1° (±3.98). The one-handed pulling posture is clearly unfavourable for pulling heavy loads, as the upper limb musculature and articulations of the pulling arm are differentially taxed. It is argued that the one-handed pulling action must be eliminated, hence the proposal of a two-handed intervention in the automotive workplace.

The integration of the 3D SSPP and ErgoImager software programmes facilitates postural and force predictions based on laboratory observations. Figure 22a and b demonstrate the one- and two-handed simulations derived from the 3D SSPP for pre- and post-intervention pulling, and estimated forces from this programme. The one-handed pulling evaluation specific to the right shoulder joint results in only 54% of population being capable of executing the 20kg.f pulling effort pre-intervention. Only 60% of the population were considered capable of completing the trial using one hand based on the 3D SSPP prediction for the elbow (Figure 22a). The 3D calculation of low back compression was estimated at 1 806N during the uni-lateral pull, and this finding together with iLMM responses which follow indicated that the action was sub-optimal.

a



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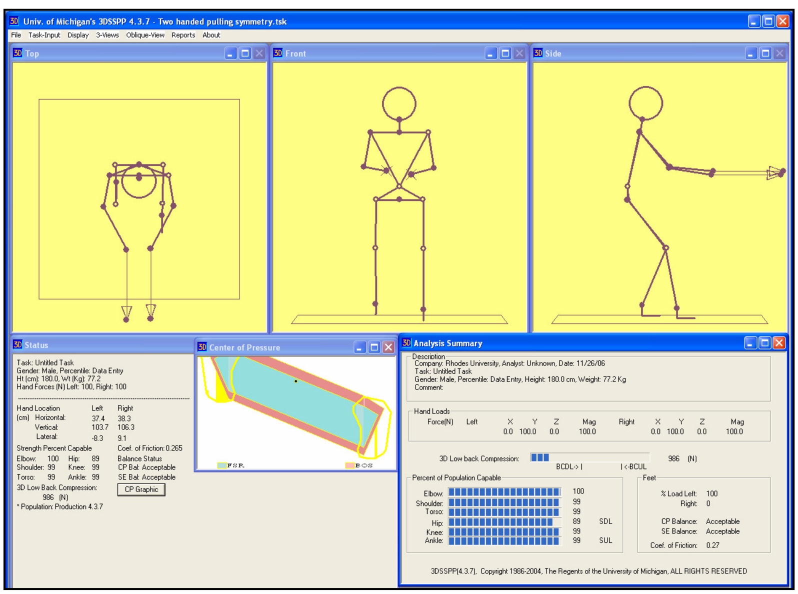


Figure 22 a and b: *3D SSPP simulation for PTT pulling laboratory experimentation pre- (a) and post-intervention (b).*

Figure 22b demonstrates the clear benefits of the intervention pulling action as the percentage of the population capable of completing the modified sub-task when considering the shoulder joint complex was 99%. The minor postural modification thus reduced the estimated musculoskeletal stresses specific to the upper limbs, and similarly the elbow value was improved from 60 to a predicted 100% post-intervention. The centre of pressure (CP) in relation to BS was unacceptable pre-intervention, but was suitably modified to allow for an acceptable level of balance during the symmetrical two-handed pull, which also reduced the compression by 55% to 986N post-intervention.

Findings from the present study concur with Lee **et al.** (1991), who argued that extreme push-pull tasks result in frequent over-exertion injuries. Excessively heavy, poorly designed and awkwardly shaped skids used in the present study increased the force output required of the workers in the Paintshop. In addition, working postures evidenced for pulling tasks have been shown to pose a considerable risk to the workforce due to the configuration of the transfer trolley, excessive lean, and the increased likelihood of slips and falls associated with these tasks. In order to eliminate the excessive use of the one-handed asymmetrical pulling action at the side of the vehicle frame, a two-handed symmetrical pull with an extended attachment was recommended. Symmetrical pulling with two hands was shown to reduce hyperextension post-intervention and place the workers in a position with considerably more control over their working postures, and consequently over the skid movement on the vehicle transfer line.

The current pushing methods predominantly in use in the Paintshop are awkward, restricted and asymmetrical, which places a large amount of strain on the dominant side (the right hand side was used for the purposes of laboratory experimentation). The uni-lateral pushing actions frequently take place above acromial height thus exacerbating the forces in the shoulder joint and often induce an excessive forward lean. The pushing intervention was thus devised to minimise unbalanced actions and encourage operators to use both hands in pushing the unit during the related sub-tasks in the Paintshop, where force and awkward posture are the major areas of concern.

Both one- and two-handed pushing is used in the workplace to overcome the mass of the vehicle frame resting on the transfer trolley. Figure 23a highlights the one-handed pushing simulation set-up used during laboratory experimentation. Similarly, the two-handed asymmetrical method (Figure 23b) was widely regarded by participants as entailing an awkward pushing action. The asymmetrical loading of the left shoulder was deemed to be particularly uncomfortable (guiding the simulated pushing action as the top hand) as the subject was required to place the left upper extremity in a sub-optimal position for force production, but this was necessary in the workplace to guide the vehicle unit once on the tracks of the transfer line. In contrast to the pre-intervention pushing actions, post-intervention pushing was balanced, controlled and equally split the load and subsequent force between the left and right sides.

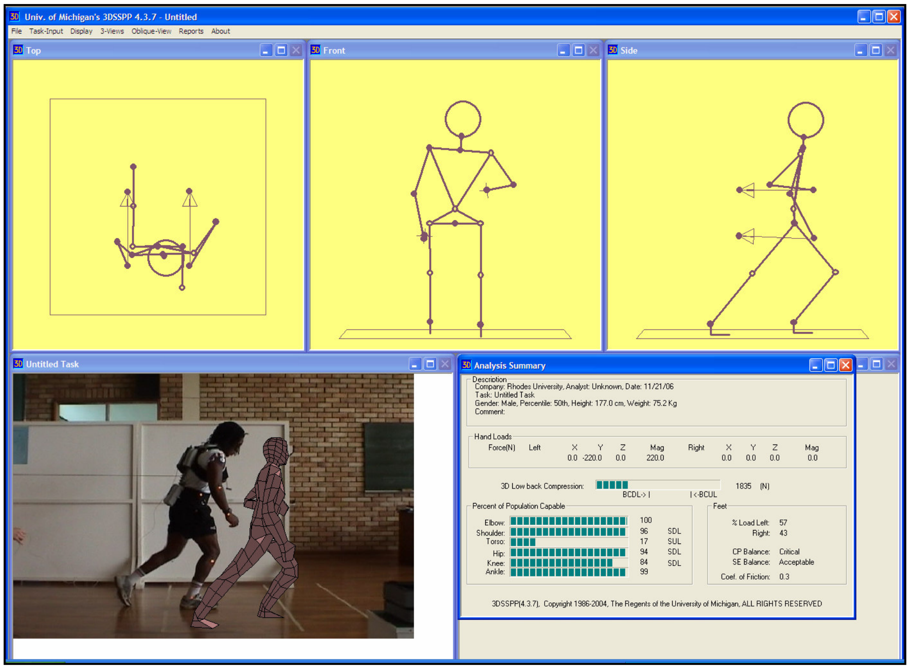
a

b

Figure 23 a and b: *Pushing working postures simulated during pre-intervention laboratory experimentation.*

3D SSPP analyses of selected pushing tasks demonstrated that the asymmetrical pushing postures for one- handed pushing pre-intervention differentially tax the upper limbs as illustrated in Figure 24a. Post-intervention analysis of the symmetrical push is shown in Figure 24b.

a



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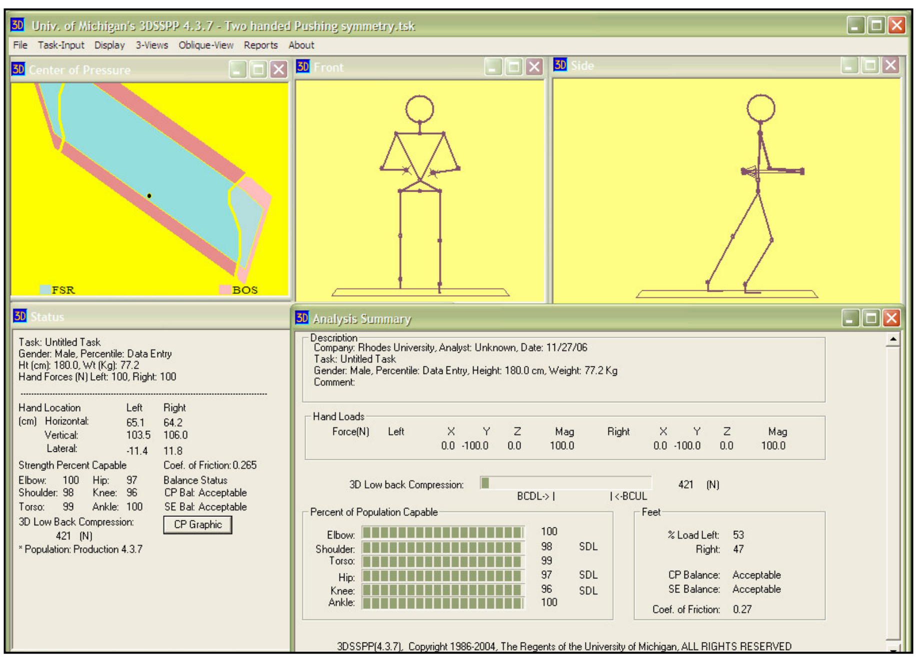


Figure 24 a and b: *3D SSPP simulation for PTT pushing laboratory experimentation pre- (a) and post-intervention (b).*

During the one-handed pushing trials the torso was in a twisted position resulting in only 17% of the population being capable of the simulated pushing action (Figure 24a). The CP was also rated as critical pre-intervention indicating that a minor stumble would result in a fall during the unbalanced pushing action. The location of the CP outside the BS is of particular concern in the workplace where a loss of balance will result in injury to the operator in the Paintshop.

Figure 24b demonstrates that the introduction of an even pushing action distributed the load between the left and right hand sides thereby reducing the twisting (percentage capable was improved from 17 to 99%), and stresses placed on the rotator cuff of the dominant limb. The 3D low back compression showed a significant reduction from 1 835N to 421N post-intervention indicating a low level of compressive forces well below the acceptable working limit. The CP balance was improved from critical to acceptable post-intervention with participants commenting on a perception of greater control over the simulated load in the laboratory experimentation phase after modifications were made to the pushing action.

Current working practices in the Paintshop place the human operator at risk of developing overuse injuries of the upper limbs, for as Hoozemans **et al.** (2004) argued, the force required to overcome a heavy load should be shared between the left and right hand sides of the body in order to reduce the risks of WRULDs. Based on the findings of the present study it is argued that in the workplace the even allocation of the load through a two-handed pushing action at the front of the skid will reduce the musculoskeletal stresses on the body and result in the vehicle frame moving away from the employee, which will in turn reduce the risk of foot run-over, and when properly controlled, reduce the probability of slips and falls.

Spinal Kinematics – Industrial Lumbar Motion Monitor (iLMM)

Table X demonstrates changes observed in one-handed, two-handed and two-handed intervention pulling and pushing kinematic responses as recorded using the iLMM. Lumbar motion analysis primarily focused on the twisting velocity, sagittal flexion and lateral velocity recorded during the push-pull trials.

Table X: *Twisting velocity, sagittal flexion and lateral velocity during the PTT pulling and pushing trials.*

Pulling	**One-handed**	**Two-handed**	**Two-handed *Intervention***
Ave Twisting Velocity (°.s^{-1})	5.6 (1.57)	1.1 (0.84)	1.4 (0.72) ^
Max Sagittal Flexion (°)	11.7 (5.15)	4.4 (2.72)	3.4 (1.96) ^
Max Lateral Velocity (°.s^{-1})	24.0 (7.63)	13.1 (5.67)	15.0 (6.27) *
Pushing	**One-handed**	**Two-handed**	**Two-handed *Intervention***
Ave Twisting Velocity (°.s^{-1})	4.6 (2.78)	3.6 (2.19)	2.8 (1.84) ^
Max Sagittal Flexion (°)	3.7 (2.47)	3.8 (2.76)	3.9 (2.30)
Max Lateral Velocity (°.s^{-1})	22.3 (6.66)	22.3 (7.40)	18.8 (6.02) ^

(Means with standard deviations in brackets, shaded area post-intervention)

* *denotes significant difference ($p \leq 0.05$) between pre- and post-intervention responses one and two-handed intervention pulling only.*

^ *denotes significant difference ($p \leq 0.05$) between pre- and post-intervention responses for one, two and two-handed intervention responses.*

Besides the high force requirements there is also evidence of a twisted posture during the one-handed pulling task, and it is argued that the current push-pull techniques increase the likelihood of slipping and tripping incidents supporting the findings of De Looze **et al.** (2000), Haslam **et al.** (2002) and Todd **et al.** (2004), who argued that poor trolley design and visual obstruction result in increased push-pull risks. Statistical analyses (one-way ANOVA) showed a significant reduction in average twisting velocity between the pre-intervention one-handed and two-handed post-intervention pulling data. This finding was expected due to the reduction in asymmetry of the two-handed pulling method. While there was no difference between the two-handed pre- and post-intervention pulling, participants preferred the intervention to the current two-handed pull observed *in situ*, as it provided a more comfortable working posture by eliminating the excessive lean during the skid pulling.

Maximal sagittal flexion was significantly reduced (by 71%) as a result of the adapted pulling style, and operators are less likely to lose their balance during the two-handed pull intervention, and will have greater control over the skid unit in the "real-world" setting. A significant difference in maximum lateral velocity indicated that the lateral bend was effectively reduced by $9°.s^{-1}$ with the two-handed pull. Participants were able to work with a balanced posture and commented on a greater level of control over the simulated load. The use of the extended rope had the effect of reducing the musculoskeletal effort required to maintain balance, and combined with the changes in working posture, reduced the potential risks of WMSDs, slipping and injuries due to skid rollovers.

No significant differences were observed between pushing methods used for maximal sagittal flexion, which was less than five degrees in all three methods (see Table X). However, maximal lateral velocity showed a significant decrease (16%) during the post-intervention two-handed push, and the mean twisting of the spine was significantly reduced for pushing post-intervention. Figure 25 demonstrates a typical example of the iLMM trial data collected during the PTT evaluation of one-, two- and two-handed intervention pushing trials with a specific focus on the twisting responses of a laboratory participant.

Key:		
(red)	*Trial 1*	*One-handed pushing*
(green)	*Trial 4*	*Two-handed pushing*
(black)	*Trial 8*	*Two-handed pushing Intervention*

Figure 25: *iLMM twist trial data for a typical participant during PTT laboratory testing of pushing.*

Average twisting velocity for the one-handed push was reduced from 7.2 to 2.0°.s^{-1} for this participant post-intervention. Lateral velocity demonstrated a significant difference during the two-handed pushing post-intervention (reduced from 20.1 to 15.5°.s^{-1}).

It is argued that these findings were due to the considerable change in working posture, equal distribution of the load between the left and right hand sides, and in turn a reduction in the force requirements for the dominant limb. The proposed symmetrical pushing action is therefore shown to be a significant contributor to improving working posture and reducing the spinal twisting required of the individual, together with less physical strain being placed on the shoulder, elbow and wrist joints when evenly distributing the force output required to move the heavy load. The reduction in spinal motion was also coupled with a reduction in physiological loading, as demonstrated by the heart rate and EMG analysis sections which follow.

The Ohio State University (OSU) LBD Risk Model enables quantitative assessment of each task within a job, and Marras **et al.** (1997) suggested that the LDB risk model may assist in the ergonomic intervention process. LBD risks were calculated for each of the six testing conditions in the PTT simulation using the OSU Risk Model. Figure 26 highlights an example from the OSU Risk Model for one-handed pulling, where the probability of LDB risk was 37%.

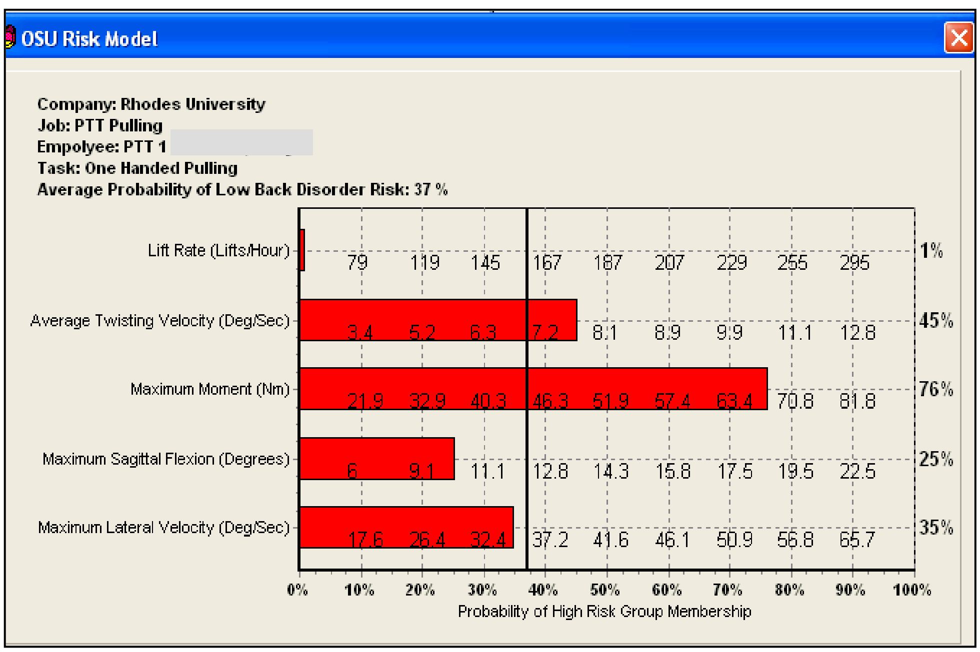


Figure 26: *OSU Risk Model graphic for a typical participant during PTT laboratory testing of one-handed pulling.*

Predictions for LBD risk were 36.8% (±8.03) for one-handed pulling simulating the pull at the side of the transfer trolley. Lower risk percentages were predicted for two-handed pulling (22.8%, ±5.49), and the two-handed pulling intervention (21.7%, ±5.31). Statistical analyses of predicted LDB risk showed a significant difference between one-handed pulling and the two-handed pulling intervention risk of LBD probability. The maximum moment (Nm) remains constant during the pushing and pulling tasks as the loading and associated force output requirements do not change. The load constant of 20kg thus has a considerable effect on the loading and motions of the spine during the pulling actions.

The decrease in anticipated risk for two-handed pulling demonstrated in Figure 27 is achieved through a reduction in average twisting velocity, acceptable maximal lateral velocity and minimal sagittal flexion post-intervention.

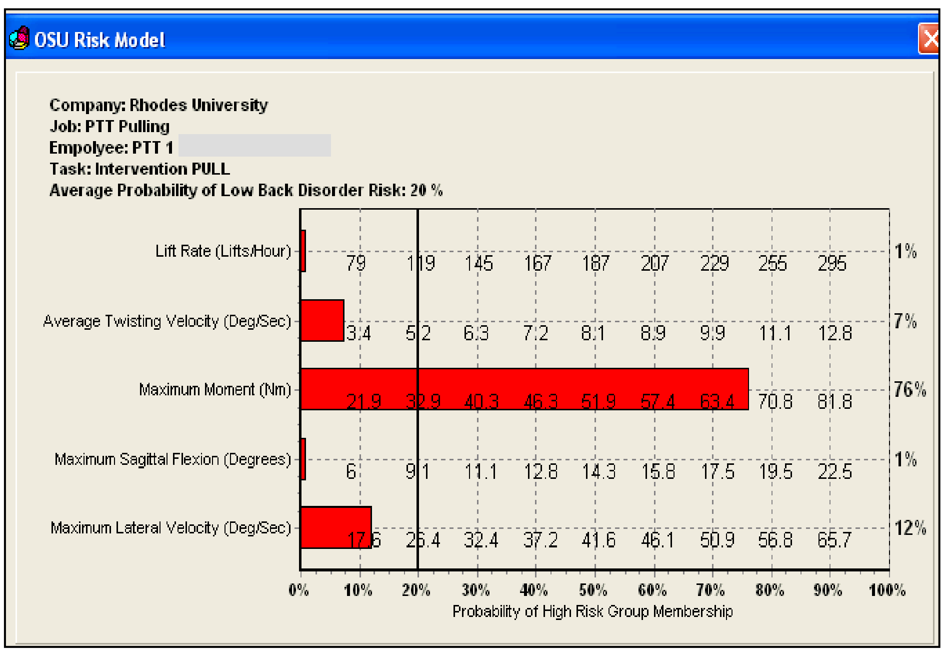


Figure 27: *OSU Risk Model graphic for a typical participant during PTT laboratory testing of two-handed pulling intervention.*

The intervention reduced the risk specific to twisting velocity from 45% to 7%, indicating a drop from 'moderate' to 'very low' risk according to the classification proposed by Marras **et al.** (2000). Due to the balanced, upright posture, lower levels of sagittal flexion were elicited during the pulling action and the probability of high risk group categorisation is considerably reduced from 25% to only 1% post-intervention. The summated risk during the two-handed pulling was reduced from 37% to only 20% post-intervention.

LBD risk for one-handed pushing was estimated at 38.2% (±4.03), and two-handed pushing LBD risk also exhibited a higher level of risk than the intervention at 33.8% (±6.73). The symmetrical two-handed pushing intervention resulted in a considerable reduction in predicted low back risk (21.9%, ±4.53). In addition, the two-handed symmetrical pushing intervention is considered preferable due to the balanced distribution of force output achieved in the upper limbs, a reduction in twisting position, velocity and acceleration, and lower predicted L5-S1 compressive forces in the spine. In similar research assessing the efficacy of pushing and pulling activities, Hoozemans **et al.** (2004) compared pushing and pulling actions, and demonstrated that predicted spinal compressive forces at L5-S1 were significantly lower when pushing with two hands when compared to pulling with one or two hands at hip height. Pushing in the range from iliac to below acromial height would appear to result in less compressive force on the L5-S1 region of the lower back, which would, according to Hoozemans **et al.** (2004), assist in the minimisation of high risk. Furthermore, the pushing action has been shown to allow the workers to use their body masses to move the load with less physical exertion and lower risk of slipping over the side of the skid unit than is the case for the current one-handed push (James and Todd, 2004; Todd, 2005).

Although potential risk of LBD may not be as prevalent during pushing and pulling as is the case for excessive manual lifting, Marras (2000) suggested that there is evidence linking any forceful movements, awkward posture and heavy physical work to WMSDs. Many authors have reported on physical loading on the lower back in the place of work, in particular high peak forces and poor trunk postures and movements have been presented as contributors of the reporting of LBD (Marras **et al.**, 1995; McGill, 1996; Davis and Marras, 2003). In the present project the lower back risk categorisation based on the work of Marras **et al.** (2000) is only placed at 'moderate' during pushing and pulling simulations pre-intervention. Nonetheless LBD risk remains a potential concern to the Paintshop workforce given the excessive physical requirements of the pre-intervention push-pull tasks.

The analyses of the responses to the PTT tasks clearly demonstrate several upper limb related risk factors which need to be controlled in the workplace, including awkward postures, uni-lateral push-pull actions, high force requirements, excessive joint loading and repetitive motions. It is therefore argued that based on consideration of biophysical parameters, the work actions specifically taxing only the dominant limb, such as the one-handed pulling or pushing tasks, necessitate immediate workplace interventions.

PHYSIOLOGICAL VARIABLES

While much of the research in MMH has focused primarily on the musculoskeletal stresses placed on the human body, it is important to get some measure of the cardiovascular responses of manual labourers, particularly in IDCs where so many of the workers suffer from poor nutrition and health associated problems.

Heart Rate Responses

Heart rate is a useful indicator of work output requirements and may be monitored via simple telemetric devices in the field or laboratory (Scott and Christie, 2004; Renz and Scott, 2004; James and Scott, 2006). Of all six conditions evaluated, the highest mean working heart rate (102.9 ± 11.62 $bt.min^{-1}$) was recorded for the two-handed push. The working posture during this trial was extremely awkward, with the left hand raised above the right hand to simulate the pushing action observed in the GM Paintshop. Figure 28 reveals that the lowest mean heart rate data were recorded for pulling during the simulated symmetrical manoeuvre of the load during the post-intervention testing phase.

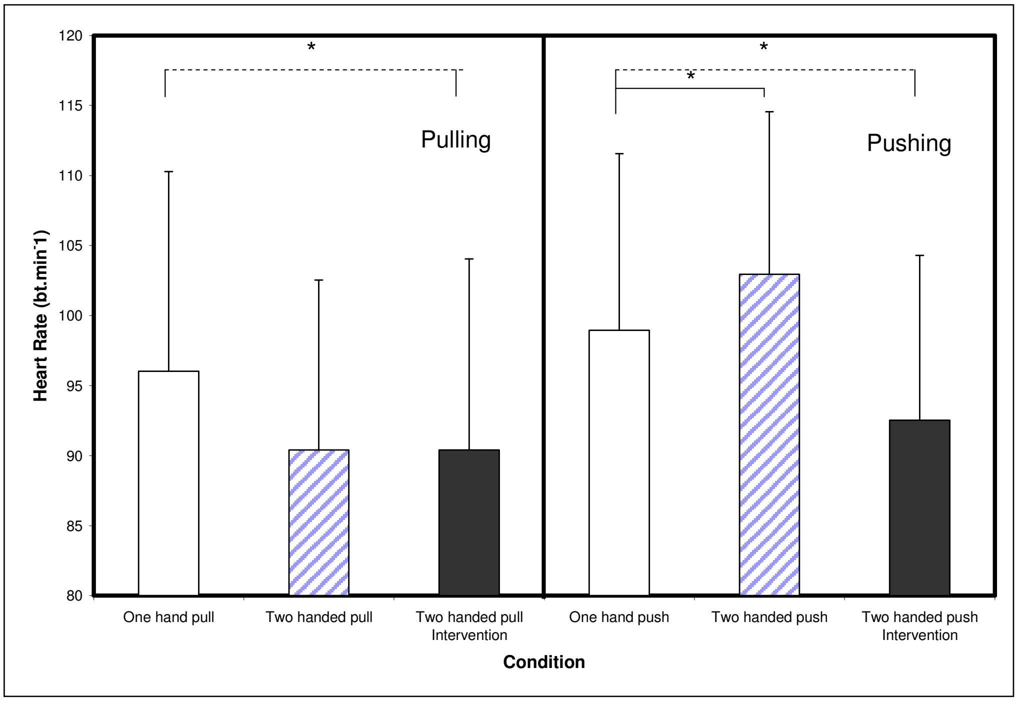


Figure 28: *Physiological responses reflected via heart rate recordings during PTT laboratory testing.*
(n=30)

* *denotes significant difference ($p \leq 0.05$) between pre- and post-intervention heart rate responses.*

Although there was a significant difference between the one-handed pull and two-handed pulling intervention (a reduction from 96.0 to 90.4bt.min^{-1}), no difference was observed between the two-handed pull (pre-intervention with an excessive lean, see Figure 21c) and two-handed intervention (see Figure 21d). This was not unexpected due to the similar method of completing the two sub-tasks. However, the two-handed pull with the extended rope, did reduce the extreme backward lean (from 23.7° ±3.51 to 13.9° ±2.21), which will ultimately minimise the likelihood of slipping and falling accidents, and reduce the risk of trolley rollover injuries, thus concurring with the findings of Haslam **et al.** (2002) and James and Todd (2003; 2006), who argued for the maintenance of an upright, balanced working stance. In addition, subjective ratings showed that the participants felt more stable during the pulling intervention, thus making this the preferable method when considering the skid pulling action.

A significant drop was observed between the one-handed (98.9 ±12.61 $bt.min^{-1}$) and two-handed pushing (102.9 ±11.62 $bt.min^{-1}$) when compared to the proposed intervention (92.5 ±11.77 $bt.min^{-1}$). Participants were clearly less taxed during the two-handed symmetrical pushing, and the subjective preference for this method of task completion was also noted amongst participants. It is argued that asymmetrical and cramped working postures, as well as unequal load distribution required during the one- and two-handed push pre-intervention clearly influenced physiological responses reflected through increases in heart rate.

These findings are similar to those of Renz and Scott (2004) and Scott and Christie (2004), whose "field-laboratory-field" investigations demonstrated the practical benefits of simple interventions on reducing the physiological strain on the work cohort reflected via a decrement in heart rate responses. Laboratory PTT heart rate responses were reduced by 10.4 $bt.min^{-1}$ and 5.6 $bt.min^{-1}$ for the two-handed pushing and pulling interventions respectively. According to the categorisation matrix proposed by Renz and Scott (2004), the average working heart rates (92.5 $bt.min^{-1}$ for the two-handed push and 90.4 $bt.min^{-1}$ for the two-handed pull) will result in 'low risk' and should be maintainable over a 7.5h working shift at the GM plant.

Electromyography - Mega EMG System

A four channel Mega ME3000P Electromyography (EMG) system was used to trace muscular activity in the *medial deltoid* (left and right) and *erector spinae* (left and right) for the PTT simulation (Task 1).

As the working postures for pushing or pulling activities pre-intervention were identified as being the most problematic due to uneven loading of the musculoskeletal system, the quantification of muscular activity in the *medial deltoid* was deemed essential in order to measure the potential reductions in this activity achieved as a result of simple workplace changes.

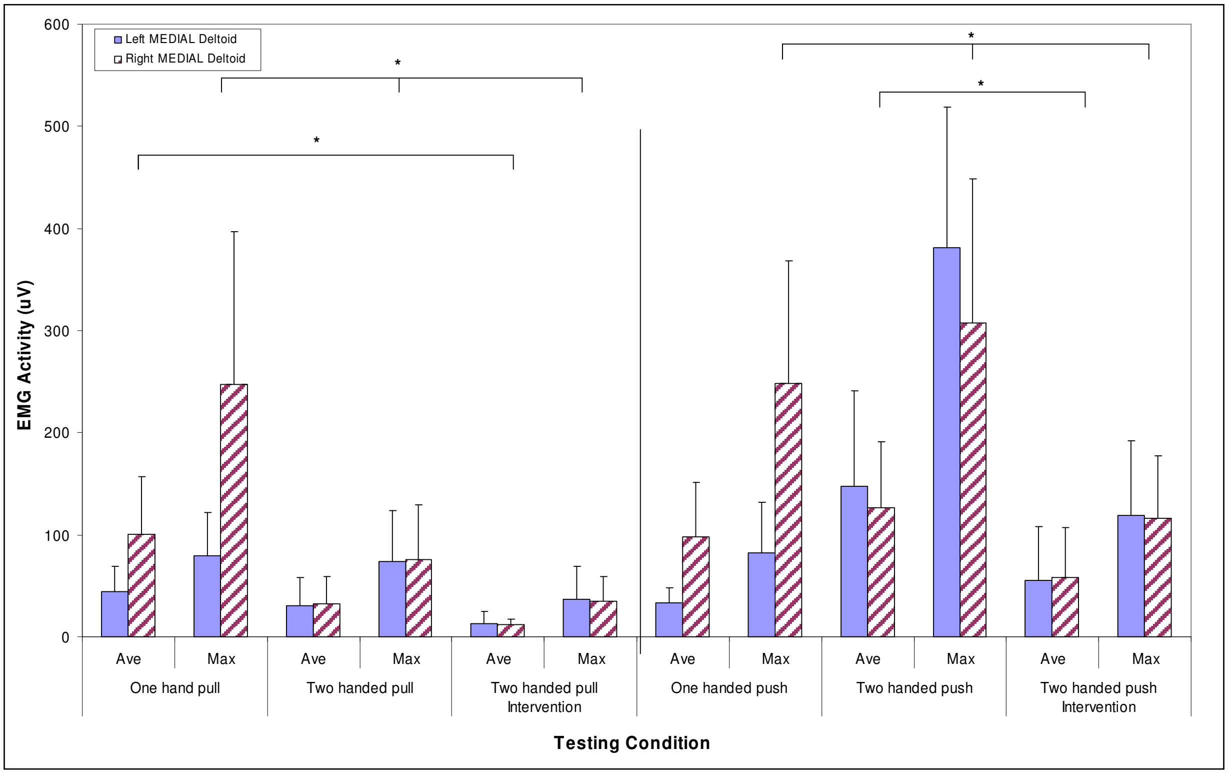


Figure 29: *Medial deltoid muscle activity reflected in the EMG recordings during laboratory testing.*
(n=30)

* *denotes significant difference (p ≤ 0.05) between one-handed, two-handed and two-handed Intervention pushing or pulling EMG responses.*

Figure 29 reveals that averaged and maximal EMG for the right *medial deltoid* were significantly reduced during post-intervention pulling. The intervention conditions clearly showed the benefits of a symmetrical pulling posture as the averaged *medial deltoid* activity was reduced from 100.1 to 11.8µV for pulling post-intervention. The two-handed pulling intervention elicited the lowest levels of muscular activity in the shoulder joint complex of all six PTT trials, indicating that the upright pulling action had the effect of evenly distributing the upper limb muscular load, as demonstrated by EMG responses.

The maximal left and right *medial deltoid* activity was recorded during the one and two-handed pushing (pre-intervention) sub-task data, with significant differences observed for both the averaged and peak activity between the original two-handed push and the proposed intervention (reduced from 148.1 to 55.3µV for two-handed trials). The averaged EMG data shows that the left and right *medial deltoids* were excessively taxed during pre-intervention pushing, which, coupled with unsafe working postures, results in a considerably higher level of risk to the participant. Post-intervention pushing demonstrated the impact of balanced loading of the *medial deltoids* with an averaged EMG activity of 55.3 and 58.4µV in left and right shoulders respectively.

EMG activity in the lower back was assessed for the left and right *erector spinae*. Various researchers have argued that it is necessary to look at the muscular activity as a percentage of maximum voluntary contraction (MVC), particularly for the left and right *erector spinae* muscles (Lehman and McGill, 2001; Garg **et al.**, 2006; Marras **et al.**, 2006). Prior to the commencement of the laboratory experimentation, maximal values were recorded during MVC for the left (467.8µV ± 139.20) and right *erector spinae* (465.6µV ± 147.20). These showed no statistically significant difference between left and right *erector spinae* activity. Table XI highlights the specific mean values for pushing and pulling as a percentage of MVC for PTT simulation.

Table XI: *Averaged EMG activity (µV) for erector spinae as a percentage of MVC during pulling and pushing.*

One-handed Pulling		**Two-handed pulling**		**Two-handed pulling Intervention**		**One-handed pushing**		**Two-handed pushing**		**Two-handed pushing Intervention**	
Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
7.6 (3.81)	6.4 (4.76)	7.9 (6.10)	7.3 (5.41)	8.0 (4.18)	7.0 (3.13)	11.2 (8.38)	8.3 * (4.72)	14.0 * (9.81)	9.0 (5.89)	11.5 (5.80)	11.0 (6.05)

(Means with standard deviations in brackets, shaded area post-intervention)

** denotes significant difference (p ≤ 0.05) between pre- and post-intervention EMG responses.*

EMG reported as %MVC demonstrated no statistically significant differences for pulling activities. One-handed pulling showed the lowest mean for the right *erector spinae* (6.4%). This response may be explained by considering the one-handed pulling action which placed a considerably greater strain on the right upper limb. The right *erector spinae* were least taxed during this activity, but a concomitant increase in muscle activity was observed in the right *medial deltoid* (as shown in Figure 29). The two-handed pulling posture resulted in balanced loading of the left and right *erector spinae,* which was expected due to the symmetrical pulling actions pre- and post-intervention. Despite the excessive lean pre-intervention the loading of the back musculature was not increased, instead greater muscle activity was recorded in the shoulder joint complex as demonstrated in the left and right *medial deltoid*. It is argued that participants increased the muscular output of the upper limbs, rather than the back, in order to overcome the simulated load, resulting in only a nominal change in *erector spinae* activation.

Statistically significant differences were observed between two-handed pushing pre- and post-intervention for the left *erector spinae*, where a reduction in loading resulted in a decrement from 14.0% to 11.5% post-intervention. However, the right *erector spinae* showed an increase in loading as a percentage of MVC from 8.3% (one-handed pushing) to 11.0% in the post-intervention test as the subjects were less reliant on the upper extremity for force production. Similarly the two-handed push pre-intervention elicited a lower EMG activity as a %MVC of 9.0%. All *erector spinae* loading levels are acceptable in terms of manual work when compared to other examples of EMG-based research, such as the work of Marras **et al.** (1998).

It may be argued that the post-intervention pulling and pushing conditions were more suitable for a number of reasons, but most importantly because of the symmetrical and controlled working posture they facilitated. Physiologically the responses of the participants also indicated much lower levels of cardiovascular and muscular loading, with reductions in both heart rate and EMG activity in the shoulder joint complex post-intervention.

PSYCHOPHYSICAL RESPONSES

Body Contribution: PTT Pulling

Table XII shows the responses for the pulling tasks (one-, two- and two-handed intervention) recorded during the present study, and these revealed that the participants rated the right upper limb as the major contributor to the one-handed pulling effort. The level of contribution was rated at 4.5 (± 1.5). Subjective responses are a useful indicator of operator preference, and the participants commented on the difficulty of completing a one-handed pull of a 20 kg using a single limb. The second area rated was the right bicep due to the force output requirement of the three repetitions of one-handed pulling (mean rating: 3.6 ± 1.3). The two-handed pulling (pre-intervention) trials required the participants to accentuate the backward lean, and as a result the area regarded as being the major contributor to the two-handed pulling repetitions was the lower back region, with a mean rating of 3.8 (± 1.4) for this sub-task. Interestingly, the quadriceps areas (19 and 20 anterior) were rated as the second area of notable contribution by 23% of the participants (mean rating: 3.0 ± 1.4). This finding indicates that participants perceive the lower extremity to be a substantial contributor to the two-handed pulling action.

Table XII: *Body contribution areas and ratings for the pulling trials.*

Trial	*Contribution*	*Area Identified*	*% of Participants Rating Area*	*Rating (Max 10)*
One-handed pulling	Greatest contribution	3 Anterior (right shoulder)	43%	4.5 (1.5) 33.40%
	2nd area	6 Anterior (right bicep)	27%	3.6 (1.3) 36.03%
Two-handed pulling	Greatest contribution	11 Posterior (lower back)	37%	3.8 (1.4) 36.17%
	2nd area	19 and 20 Anterior (quadriceps)	23%	3.0 (1.4) 46.28%
Two-handed pulling Intervention	Greatest contribution	23 and 24 Posterior (calves)	23%	3.9 (1.6) 41.16%
	2nd area	19 and 20 Anterior (quadriceps)	20%	2.9 (1.2) 41.71%

(Means with standard deviations in brackets, % = coefficient of variation, shaded area post-intervention).

Using the extended rope attachment (the post-intervention method for the two-handed pull) required the participant to adopt a balanced, more upright posture, while moving the simulated load, and resulted in 23% of participants indicating that regions 23 and 24 Posterior (calves) were the greatest contributor to the pulling efforts post-intervention (mean rating: 3.9 ±1.6). It is clear the intervention strategy transferred the emphasis of muscular effort from the more gracile upper extremities to the more robust musculature of the lower extremities. Given the relative strength of the lower extremity in contrast to, for example, the shoulder joint complex, it would be advisable for the operators in the

Paintshop area to pull using a symmetrical posture and minimise the joint loading of the upper extremity rather than use the one-handed pulling action as observed *in situ*, for as Huisstede **et al.** (2006) suggested, WRULDs remain a problem in the workplace where poor postures are widespread. Educating the workforce at GM in appropriate pulling or pushing methods was thus prioritised as a focus for the post-intervention application of the laboratory based findings for the present study.

Body Contribution: PTT Pushing

The mean ratings recorded using the body contribution map and rating scale for pushing are presented in Table XIII. The body areas associated with the one-handed pushing, that is the right bicep and right shoulder, were rated most frequently due primarily to the working posture required for the push and the reliance on the upper extremity to overcome the initial mass of the load. With the two-handed pushing the left triceps and right bicep were the major contributors to the pushing action, as the pushing action was completed slightly ahead of the body to simulate musculoskeletal loading as observed in the automotive plant.

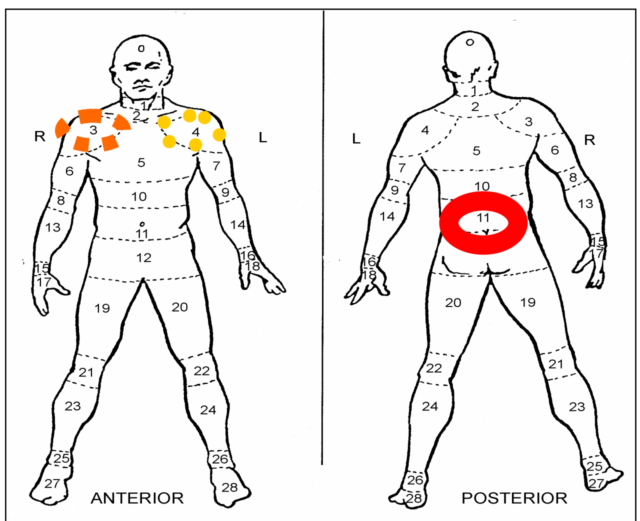
Table XIII: *Body contribution areas and ratings for the pushing trials.*

Trial	***Contribution***	***Area Identified***	***% of Participants Rating Area***	***Rating (Max 10)***
One-handed pushing	Greatest contribution	6 Anterior (right bicep)	33%	4.7 (1.6) 32.79%
	2nd area	3 Anterior (right shoulder)	23%	3.9 (1.3) 32.44%
Two-handed pushing	Greatest contribution	7 Posterior (left triceps)	23%	4.5 (1.5) 32.63%
	2nd area	6 Anterior (right bicep)	23%	3.8 (1.5) 40.32%
Two-handed pushing Intervention	Greatest contribution	6 Anterior (right bicep)	20%	4.0 (1.7) 43.55%
	2nd area	19 and 20 Anterior (quadriceps)	13%	3.0 (1.3) 44.59%

(Means with standard deviations in brackets, % = coefficient of variation, shaded area post-intervention)

Body Discomfort: PTT Pulling and Pushing

Areas and ratings of body discomfort are shown in Figure 30, which also provides an indication of the percentage of the sample identifying discomfort in the area under consideration. Greatest discomfort in both the pushing and pulling simulation activities was experienced in area 11 (posterior, lower back), which was singled out by 33% of participants. The mean rating of 4.8 (± 1.8) indicates that the levels of discomfort were moderate and most participants were able to complete the sub-tasks without undue discomfort. The second and third areas of discomfort were the anterior right and left shoulders respectively. Only 13% of participants rated right shoulder discomfort (mean rating: 4.2 ± 1.6), while for the left shoulder 10% of the sample experienced mild discomfort (mean rating: 3.0 ± 1.6).



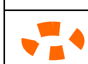
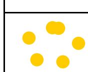
Key:	Rating	Area:	% of Participants Rating Discomfort in Area
	Greatest Discomfort	11 Posterior (Lower Back) (Mean Rating: 4.8 SD 1.8)	33%
	2nd area	3 Anterior (Right Shoulder) (Mean Rating: 4.2 SD 1.6)	13%
	3rd area	4 Anterior (Left Shoulder) (Mean Rating: 3.0 SD 1.6)	10%

Figure 30: *Body discomfort ratings (top three areas) recorded following the completion of the PTT (Task 1: Condition A). (n=30)*

The comparison of body discomfort ratings recorded in the laboratory to those of the workers *in situ* shown in Figure 18 reveal a similar perception of body discomfort between experienced operators and naïve laboratory participants, with the lower back being the most frequently rated area. The mean intensity of discomfort experienced was 5.5 (± 1.9) during the first hour, and increased 5.8 (±1.7) during the second hour of *in situ* observation. The laboratory mean rating was 4.8 (±1.7) for the same region although the period of experimentation was notably shorter in duration.

The lower extremities were more frequently rated in the field when compared to the laboratory, which may well be explained by considering the sampling time in the field (over a 2h duration) as opposed to the laboratory where participants were completing a rigorously controlled experiment where the aim was to minimise the effects of fatigue on responses.

SUMMARY

Task 1: Paintshop Trolley Transfer (PTT) Simulation

'Dynamic pushing and pulling' is an area which requires further research in order to advance the level of understanding of the effects of task demands on the musculoskeletal system, and the incidence of S, T and F accidents (Jansen **et al.,** 2002; Todd, 2005). Asymmetrical pushing has been shown to be the most demanding in terms of the upper extremity, with the rotator cuff particularly being taxed during the one-handed pulling, one-handed pushing and two-handed pushing, and the present study has highlighted the importance of symmetrical pushing or pulling in order to change spinal kinematics, physiological responses and perceptual ratings of those involved in such actions. It has been proposed that pushing or pulling with one hand places considerably more loading stresses on the dominant upper limb completing the given activity with the results collected sustaining the arguments of Colombini (1998), Muggleton **et al.** (1999), and Buckle and Devereux (2002), who suggested that repetitive, awkward work will increase the likelihood of problems associated with upper limb work.

The intervention strategies proposed here suggest that the demands placed on the operator in the field will be reduced if the working methods are altered and sub-optimal working postures eliminated. The evidence for this is provided by reductions in levels of spinal motion, particularly in reductions of the twisting action evidenced in the one-handed pulling sub-task. Secondly, the physiological responses were reduced with the introduction of modified pushing and pulling methods as reflected in the lower ‘working’ heart rate and EMG responses.

Perceptual responses also indicated the benefits of the proposed interventions where participants were required to rate their preferred method of task completion. The majority of participants (90%) rated the intervention strategies as their preferred method of pushing or pulling task completion. The exceptions to this were individuals who desired greater flexibility in the two-handed pulling trials, and in fact preferred the exaggerated leaning posture during the completion of this sub-task. Although the angle of lean could be controlled in the laboratory, a potential concern when considering the application of the extended rope or skid attachment in the field, where the surface is uneven and there are tracks which have to be stepped over, is that operators will revert back to an extreme lean and thereby increase their level of risk if this is not properly controlled. The education of the workforce in the Paintshop as to the preferable working methods is therefore regarded as essential during the implementation of the intervention *in situ*.

Task 2: Car Door Carriage (CDC) Bodyshop Simulation

The Bodyshop Closure Line simulation (Task 2) required the completion of the GM Corsa (Gamma) vehicle model door lift, carry and place as observed in the Bodyshop area of the assembly process. Participants were required to cover the same carrying distance as measured *in situ* and work at the same pace as recorded in the plant for the pre-intervention car door carriage (CDC). Post-intervention treatments assessed an alternative method of task completion, that is the use of a simple, low-cost trolley.

BIOPHYSICAL PARAMETERS

Working Posture Analyses

The vast range of kinematic responses for the CDC sub-tasks required consideration of the working postures adopted by the participants, therefore postural analyses were conducted on pre- and post-intervention lifting (sub-task i), pre-intervention carrying or post-intervention trolley pushing (sub-task ii) and pre- and post-intervention car door placement (sub-task iii). The benefits of the post-intervention strategy are demonstrated in the figures that follow, where typical examples have been selected to illustrate the key changes in working posture achieved by applying the intervention strategy for the CDC lifting phase of laboratory experimentation.

Uncomfortable working posture has been shown to be a major contributor to workplace discomfort (Marras, 2000), and any sagittal motion from the vertical, such as lifting a door from a large industrial storage bin as observed in the Bodyshop, will significantly increase the moments and shearing forces acting on the lumbar spine. The intervention strategy aimed to reduce the spinal motions by making minor adjustments to the lifting height, work organisation, storage bin space, and consequently the working posture required of the operator during sub-task i.

No restrictions were placed on the lifting style selected by laboratory participants. However, coupling points for the left and right hands were clearly demarcated on the car door, which resulted in a similar level of hand asymmetry at the point of origin of the lift. Figure 31 shows the contrasting lifting styles selected pre- and post-intervention for sub-task i. The lifting styles adopted in the lift have been classified into ‘squat’, ‘semi-squat’ and ‘stoop’ for the purposes of categorisation.

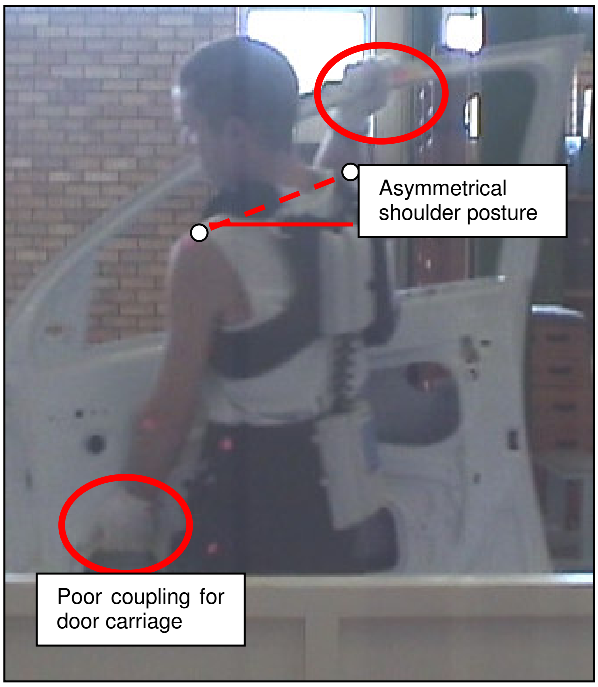
Given the storage position of the door in the bin, there were very few participants who adopted a ‘semi-squat’ or ‘stoop’ lift. The majority of participants (80%) adopted a ‘squat’ lift in the pre-intervention phase.

Pre-Intervention	**Post-Intervention**
	
a *'Squat' lift*	***b*** *Reduced 'squat' lift*
	
c *'Semi-squat' lift*	***d*** *Reduced 'semi-squat' lift*
	
e *'Stoop' lift*	***f*** *Reduced 'stoop' lift*

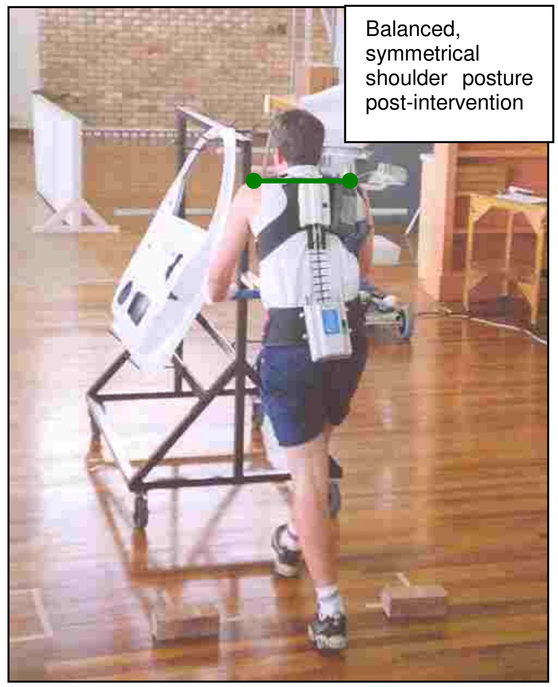
Figure 31 a, b, c, d, e and f: *Working postures selected while lifting the car door pre- and post-intervention in the laboratory.*

Pre- versus post-intervention postural analyses highlighted a reduction in sagittal flexion in the proposed ergonomics intervention lifting trials. In addition, the elimination of the step up and into the bin resulted in a notable reduction in the overall level of anticipated risk to the operator. Stepping into the modified bin required a smaller step to lift the door from a raised pallet (150mm). It is argued that this minor alteration with the bin would reduce the loading of the musculoskeletal system, risk of tripping, product damage, and also the work cycle time.

Field evaluation of door carrying showed that workers used one hand, carried the door above the head, and lifted the door on the edges with poor coupling. The simulated working posture used in the laboratory during sub-task ii (carriage or trolley push) varied substantially pre- and post-intervention. The carriage of the door (pre-intervention) and the trolley push are demonstrated in Figure 32.



a



b

Figure 32 a and b: *Working posture adopted while transferring the car door pre- (a) and post-intervention (b) in the laboratory.*

The twisting and lateral bending of the spine were identified as high risk factors during field work and were prioritised for further investigation in the laboratory. Twisting was particularly prevalent when the worker was required to rapidly move the upper body to the left or right hand sides while carrying the door in order to miss obstacles such as jigs and other operators due to the workplace congestion on the Closure Line. Pre-intervention carriage of the car door in the laboratory was therefore asymmetrical, with the right hand positioned above acromial level, and the left hand placed in the predefined lifting coupling, as shown in Figure 32a. The mean angle of asymmetry between the left and the right shoulders was 21.3° (±3.28) (see Appendix D). In contrast the introduction of a transfer trolley resulted in a balanced, symmetrical posture and eliminated the need to physically carry the 21kg door, as demonstrated in Figure 32b. Findings for the present study concur with Ciriello (2004), who suggested that a well-designed trolley or cart could be used to move heavy loads with forces that are acceptable to the majority of the workforce, thereby reducing the loading of the musculoskeletal system.

The maximal lateral reach or span that each participant was required to work at while completing the carry was 1 794mm (±61.51), which was calculated to be at the 67th percentile for the group. As Pheasant (1996) proposed that ideally the percentile of lateral reach should not exceed 50% of maximal span to maintain an acceptable working posture which will not differentially tax the upper limbs, it is clear that the span necessitated for carrying the door pre-intervention was well in excess of this guideline.

3D SSPP postural analyses and force predictions were carried out for pre- and post-intervention car door transfer sub-tasks. The key findings from this theoretical prediction package are demonstrated in Figure 33a and b. The primary articulations of concern during the pre-intervention vehicle part carriage were the shoulder and torso. The elevated positioning of the right hand during the door carriage phase resulted in undesirable loading of the shoulder joint complex (only 44% of the population capable) which together with higher twisting responses recorded by the iLMM result in a high-risk classification, and in addition placed the CP of the participant in the unacceptable category. Twisting of the torso resulted in a predicted 46% of the population being able to complete the door carriage task pre-intervention. Predicted 3D low back compression was 3 589N during the initial sub-task where the laboratory participant was required to manually carry the vehicle part on the simulated line.

a

b

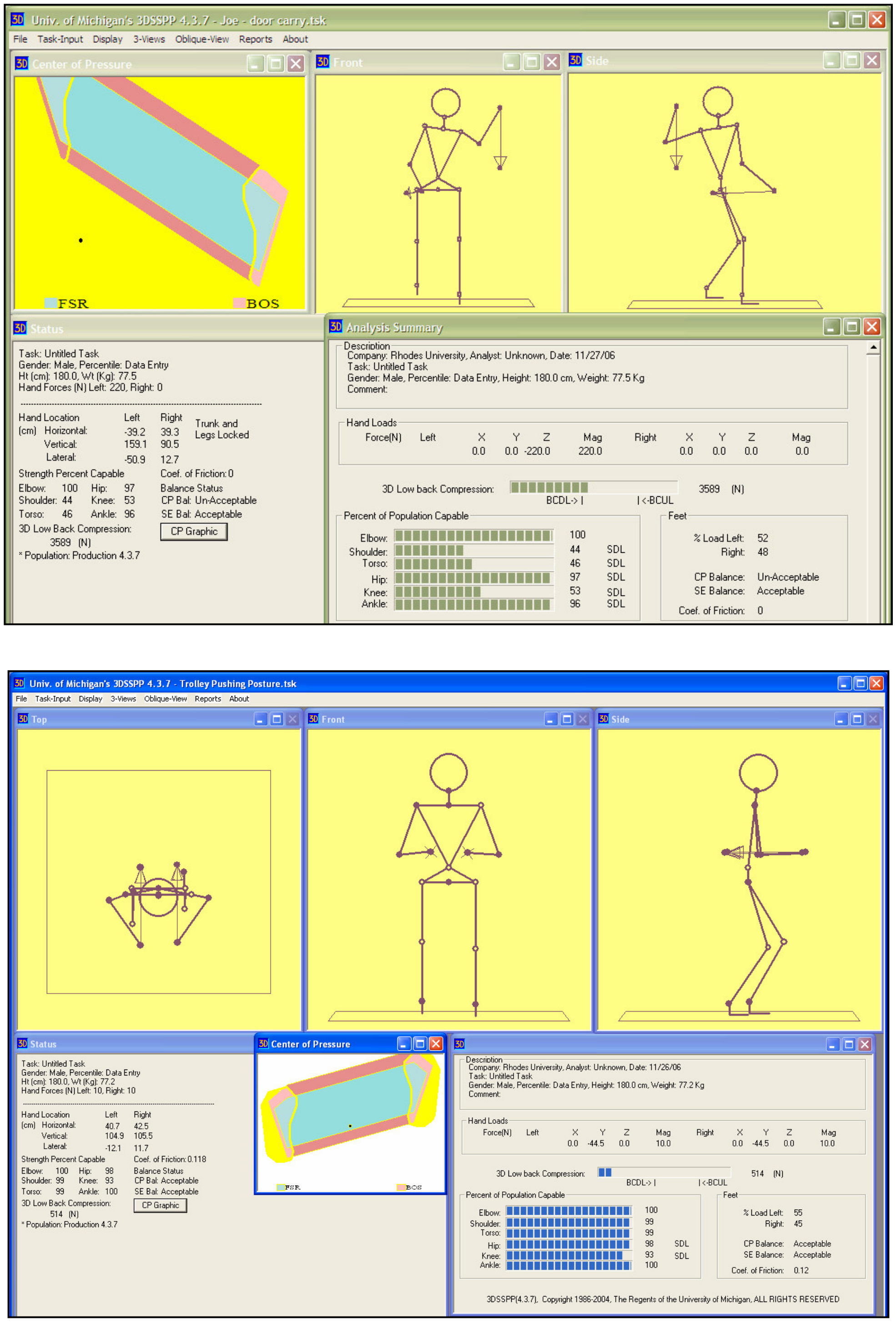


Figure 33 a and b: *3D SSPP simulation for CDC laboratory experimentation pre- (a) and post-intervention (b).*

Figure 33b illustrates the post-intervention trolley pushing action modeled using the 3D SSPP programme. The introduction of the transfer unit resulted in an even pushing posture notably reducing the uni-lateral loading of the right shoulder following the intervention. The percentage of the population capable when considering the shoulder joint was subsequently increased from 44% to 99% post-intervention. The awkward posture in the original door carriage was also eliminated with the torso percentage capable increasing from 46% to 99% when participants used the door trolley. The trolley pushing posture positioned the participant with an acceptable CP balance following the work modification. The CP was located within the BS during the transfer trolley push thereby decreasing the risk of stumbling while moving the door. It is further argued that the vision of the worker will not be obstructed during the trolley push as is the case during the manual door carriage evidenced in the Bodyshop field observation.

The most notable reduction post-intervention was in the predicted 3D low back compression which was reduced from 3 589N to 514N when the door was moved using the transfer trolley. The cumulative load on the lower back will therefore be considerably reduced during the working shift where up to 70 doors or more are manually carried on the Closure Line.

Working posture analyses for sub-task ii (trolley push) indicated that there was a notable reduction in the main risk factors proposed by Buckle and Devereux (2002) for WRULDs, including reductions in awkward posture and force output. Bridger (2003) argued that eliminating sub-optimal carriage will reduce postural stress and physiological cost of load carriage. *In situ* application of the trolley will therefore result in a considerable decrease in physiological cost and increase the working efficiency and rest periods available to the workforce.

The placement of the door (sub-task iii) was comparable pre- and post-intervention. The position of the jig and the placement height were deemed to be acceptable and changes were not proposed to the present Closure Line design, hence working postures were similar pre- and post-intervention.

Spinal Kinematics – Industrial Lumbar Motion Monitor (iLMM)

From observations (digital recordings) in the field it was noted that lifting, carrying and placing of the car door differentially loaded the spine of the operator and rigorous analysis of the participants in the laboratory confirmed these findings. The literature is replete with information to support the fact that changes in position, velocity and acceleration increase the likelihood of low back injury in the workplace (Marras, 2000; Ferguson **et al.,** 2002). The iLMM provides a useful tool for the evaluation of lifting, carrying and placement spinal ROM. The telemetric iLMM unit was well suited to the assessment of the CDC sub-tasks, and the lifting sub-task in particular is comparable to previous investigations such as the work of Ferguson **et al.** (2002).

Table XIV shows the changes in position recorded during the CDC lifting (sub-task i).

Table XIV: *Changes in position during the lifting (sub-task i) CDC trials.*

Sub-task i	Position (°) Lateral	Sagittal	Twist
Pre-Intervention	**-8.2** **(4.84)** **Min -18.2** **Max 4.3**	**28.0** **(4.78)** **Min 16.8** **Max 36.7**	**5.8** **(3.49)** **Min 0.4** **Max 15.5**
Post-Intervention	**-8.1** **(4.48)** **Min -15.9** **Max 0.2**	**20.7*** **(5.65)** **Min 12.3** **Max 29.5**	**2.6*** **(3.32)** **Min -4.3** **Max 9.2**

(Means with standard deviations in brackets, shaded area post-intervention))

** denotes significant difference (p≤0.05) between pre- and post-intervention responses.*

The storage of the car door in the bin necessitated an average level of sagittal flexion of 28.0° (± 4.78) for the pre-intervention lift. The lifting posture adopted clearly influenced the level of sagittal flexion during the CDC lift. A range of 16.8° to 36.7° was observed for the pre-intervention phase, depending largely on whether a 'stoop', 'semi-squat' or 'squat' lift was chosen as the preferred lifting style. Minor changes in the storage height of the door, where it was raised by 150mm in the bin, resulted in a significant reduction in sagittal flexion post-intervention (20.7° ± 5.65), as the participants did not feel the need to move into a deep ‘squat’ or ‘stoop’ lift from the modified position (as shown in Figure 31, p130).

Another important finding was that the mean twisting position was significantly reduced post-intervention, where participants were able to turn without restriction due to the change in storage where the side of the bin was removed. This small change in the industrial storage bin resulted in a decrease in mean twist position from 5.8° to 2.6° in the CDC experimentation. Although this was not a substantial change, coupled with the reduction in forward bend this modification reduced not only compressive forces on the spine but also shearing and torsional forces, which are a critical factor in lifting activities, for as Marras (2000) pointed out, the spine is less tolerant of shearing forces. A further benefit of the post-intervention lifting condition was the removal of the ‘step-in’ and ‘step-out’ of the bin, which was identified as a major risk in the GM Bodyshop. James and Todd (2004) have reported that trips and falls are more likely in areas where the operator is required to move from a higher to a lower level in a confined space, and the result of this adjustment to the crate was a reduction in twist and maintenance of an acceptable lateral bend (mean lateral bend to the left -8.1, ±4.02) post-intervention.

Figure 34 a and b demonstrate a typical example of the iLMM trial data collected during the CDC evaluation of pre- (a) and post-intervention (b) lifting trials with a specific focus on sagittal responses. Maximal sagittal flexion was reduced from 34.0° to 17.8° in this specific example. In addition, the original work cycle time to step into the bin, lift and step out of the crate was approximately 8s, and the intervention work cycle time was reduced to 4s post-intervention due to the appropriate placement of the door and elimination of the step into and out of the storage bin. Although the printouts are only of one subject, they do clearly demonstrate that sagittal flexion, velocity and acceleration were reduced as a result of the intervention strategy, which in turn must decrease the overall level of risk to the participant.

a

b

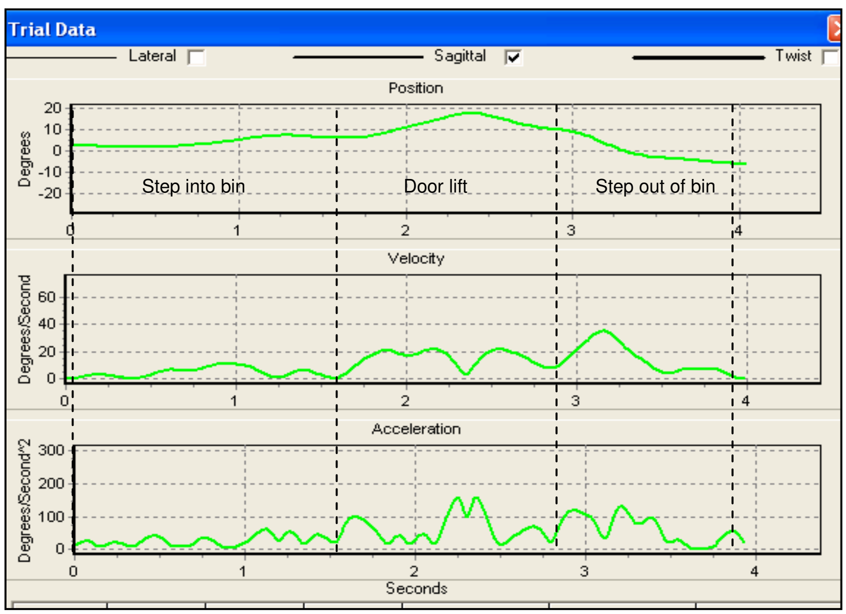


Figure 34 a and b: *iLMM sagittal trial data for a typical participant during CDC sub-task i pre- (a) and post-intervention (b).*

The University of Michigan 3D SSPP is used to predict static strength requirements and is useful in heavy MMH tasks which are performed slowly. Predictions based on rapid motions will have lower levels of reliability (3D SSPP Manual, 2004). The 3D SSPP programme was used to assess the three primary lifting methods observed in the present study, namely ‘squat’, ‘semi-squat’ and ‘stoop’. Predicted low back compression values for sub-task i (CDC pre-intervention) were 5 340N for the ‘squat’, 4 832N for the ‘semi-squat’, and 5 242N for the ‘stoop’ lift. These calculations were based on hand loads of 110N (left) and 100N (right) while lifting the front car door. The minor changes in posture while lifting the door resulted in reductions to 3 523N (‘reduced stoop’), 3 351N (‘reduced semi-squat’) and 3692N (‘reduced squat’). All lifting tasks showed a notable reduction in predicted low back compression post-intervention based on the 3D SSPP predictions.

The OSU LBD risk model (Marras **et al.**, 1997) averages moment, frequency of lift, sagittal flexion, twisting velocity and lateral velocity to predict the probability of high risk group membership for any recurring task. OSU risk model values were calculated based on each of the lifting trials (sub-task i) completed by the laboratory participants pre- and post-intervention. Predictions of average probability of LBD risk were 50.3% (±5.91) for pre-intervention and were significantly reduced to 39.8% (±5.10) for post-intervention lifting. Simple changes in the current working requirements and posture thus resulted in a reduction in LBD risk of 10.5% in the post-intervention phase. This finding is of particular relevance to the automotive sector generally as it assists in the quantification of high risk group probability and justifies the proposed workplace changes.

The carriage of the door (sub-task ii) on the Closure Line was identified as a major concern due to awkwardness of the door, space restrictions and potential hand injuries resulting from sharp edges, particularly to the left hand of the worker. The intervention strategy therefore aimed to eliminate the manual carriage of the door through the use of a transfer trolley which, once on the plant floor, could be used to move more than one door at a time. Table XV shows the changes in spinal acceleration observed during the carriage and trolley push experimentation. Significant reductions in lateral, sagittal and twisting acceleration were observed post-intervention.

Table XV: *Changes in acceleration during the carrying or trolley push phase (sub-task ii) of CDC trials.*

Sub-task ii	Acceleration (°.s^{-2}) Lateral	Sagittal	Twist
Pre-Intervention (Door Carry)	49.2 (17.32) Min 27.5 Max 94.3	34.0 (18.57) Min 9.7 Max 54.8	12.8 (7.72) Min 3.3 Max 36.2
Post-Intervention (Trolley Push)	33.6* (20.16) Min 10.8 Max 68.7	23.7* (10.98) Min 10.5 Max 50.6	7.3* (3.02) Min 2.2 Max 29.1

(Means with standard deviations in brackets, shaded area post-intervention)

* *denotes significant difference (p≤0.05) between pre- and post-intervention responses.*

The method currently used in the Bodyshop results in the operator twisting (either to the left or right, depending on the side of the line, see Figure 14, p94) while carrying the door to the jig. The trolley eliminates a high level of the twisting of the spine which will subsequently reduce the risk of injury. It was not only twisting acceleration that was reduced, but also the twisting position, where the mean recorded pre-intervention was to the right at 17.1° (± 4.26), while post-intervention the trolley placed the participant in a symmetrical position for pushing the trolley with a mean twisting position to the right of 0.9° (± 3.36).

This marks a reduction in twisting which had previously been identified as a major contributor to rendering the spine vulnerable to the compression and shearing forces acting on it (Marras and Mirka, 1989). Marras and Mirka (1990) suggested that during twisting actions, such as carrying the door asymmetrically in the present study, muscular control shifts from the collectively larger *erector spinae* muscles to the *latissimus dorsi* and the external and internal *oblique* muscles of the trunk, ultimately affecting strength, force exertion capabilities and motor control. The elimination of the load carriage phase in the CDC sub-tasks will play a significant role in reducing the loading of the musculoskeletal system. Velocity measures showed no significant differences pre- and post-intervention, which was expected due to the participants being required to move at as natural a pace as possible with a normal gait pattern along the simulated line during the carriage or trolley push.

The final placement of the car door (sub-task iii) was comparable for the pre- and post-intervention sub-tasks, as the placement on the jig could not be fundamentally changed due to the current work requirements in the Closure Line. Velocity and acceleration were not significantly reduced post-intervention. The only statistically significant change was measured in twisting position where the mean twist was reduced from 4.7° (± 4.27) to 0.6° (± 2.17), which may be attributed to the request for participants to step and turn from the trolley (post-intervention), as opposed to twist as was the case for the pre-intervention final placement of the door.

The analyses of changes in spinal kinematics for the CDC show a number of reductions in spinal motions post-intervention. Statistical analyses focused on the sagittal and rotational kinematic variables as they relate to the three sub-tasks (lift, carry and place). Twisting was significantly reduced as a result of the use of the transfer trolley, which has an added benefit to the company and employee as more doors may be moved with less physical effort.

PHYSIOLOGICAL VARIABLES

Heart Rate Responses

Tasks which require whole-body motions such as heavy lifting increase the demand for blood to transport oxygen to the working muscles (Renz and Scott, 2004) and the carriage of the car door was a whole-body activity, with participants awkwardly carrying 21kg door. The laboratory participants were required to adhere to a strictly controlled pacing schedule and complete the three sub-tasks in 30s with the aid of the transfer trolley. As the time taken to load the door-frame onto the trolley and then remove it after pushing it for 6.5m was longer in duration, the pace of the walk while pushing the trolley was increased, which had the effect of elevating heart rates. Statistical analyses via related t-Tests showed an overall significant difference between the pre- and post-intervention heart rate responses. The mean working heart rates recorded during the

10 minutes of door carriage were 119 bt.min^{-1} (±16.53), and 125 bt.min^{-1} (±15.85) during the trolley push. The work simulation had to retain the 30s cycle to control laboratory conditions while moving one door at a time, which resulted in an increase in pace, which in turn had an effect on heart rate. Differences in heart rate responses were evident in the first eight minutes of testing; thereafter participants appeared to get into a sound working pattern, resulting in a controlled trolley push at an acceptable pace during the final two collection periods.

Within the plant, the provision of the trolley will allow the operator to move more than one door at a time and reduce the overall working cycle time. It is therefore expected that the *in situ* physiological cost of the task will be substantially reduced by moving either two or four doors at a time in the Bodyshop.

Electromyography - Mega EMG System

EMG data were recorded for the left and right *erector spinae* muscles of the lower back (see p76) for the Bodyshop CDC simulation (Task 2). In order to assess the maximal EMG activity recorded in the left and right *erector spinae* muscles, MVC measures were recorded at the commencement of the CDC session. The MVC values recorded showed no statistically significant difference between left and right *erector spinae*, with the mean values being 377.6µV (± 109.37) for the left and 380.2µV (± 114.97) for the right, and maximal values being 467.8µV (± 139.20) and right as 465.6µV (± 147.20). Measured MVC values were subsequently used to express EMG activity during min3, 6, and 9 as a percentage of maximal recordings. Statistical analysis of the complete task of lift, carry/trolley push and placement showed a significant difference between pre- and post-intervention levels of mean *erector spinae* activity as a percentage of MVC. The key finding with regards to EMG analysis was that the introduction of the trolley notably reduced the overall levels of muscular activity recorded during the post-intervention CDC, particularly during the trolley push phase. Figure 35 graphs the changes in EMG responses as a percentage of MVC pre- versus post-intervention during the CDC.

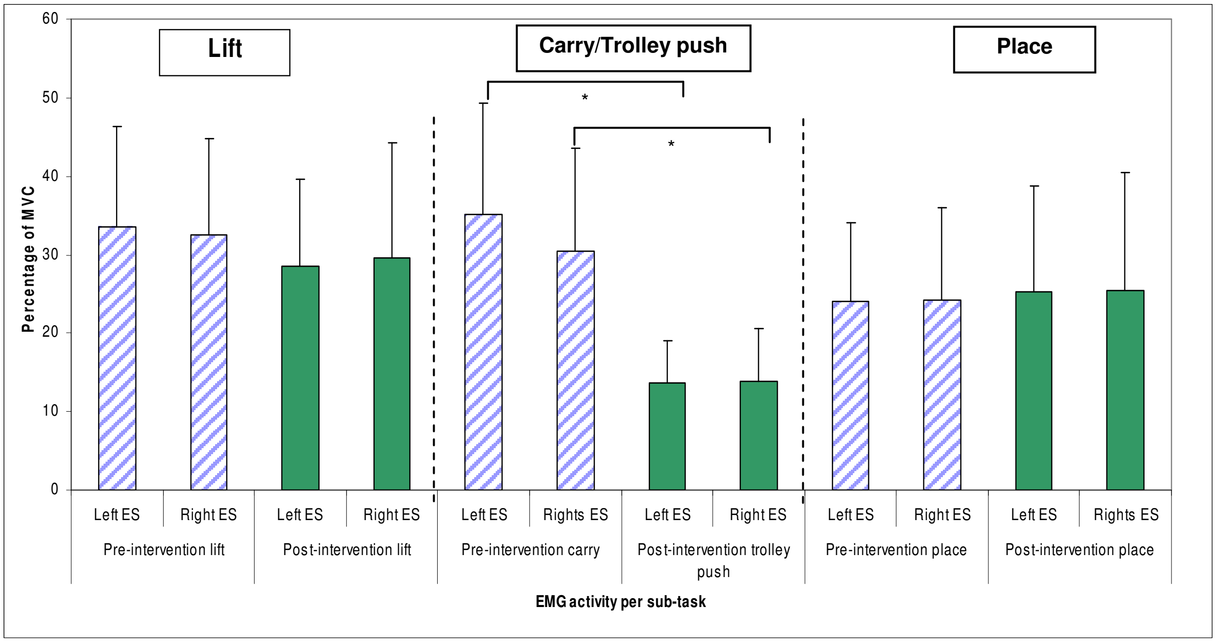


Figure 35: *EMG responses (reported as % of MVC) recorded during CDC laboratory testing. (n=30)*

* *denotes significant difference (p ≤ 0.05) between pre- and post-CDC EMG responses.*

Sub-task i (car door lifting) showed that no difference in EMG activity was evident post-intervention for both the left and right *erector spinae* due in principle to the same load requirements (21kg lifted) during the lift from the simulated storage bin. Findings in the present study are similar to the work of McKean and Potvin (2001), which assessed the effects of a simulated industrial storage bin (similar to the container in Figure 1, p19) on lifting and lowering posture and trunk extensor muscle activity. In many cases the operator is required to 'stoop' and 'reach' into the storage bin during the execution of the working cycle thereby increasing trunk muscle activity. Mean EMG recordings illustrated in Figure 35 are higher when lifting is constricted through poor bin design and sub-optimal placement of the object during the pre-intervention lift.

Statistical analyses of the carrying and trolley push (sub-task ii) showed a significant difference between pre- and post-intervention levels of left and right *erector spinae* EMG activity as a percentage of MVC. The considerably lower mean levels of muscular activity (reduced from 35.1% to 13.7% for the left *erector spinae*) were associated with the introduction of the transfer trolley for the carriage phase of the CDC (sub-task ii). During the pre-intervention carry the majority of the load was taken by the right shoulder joint and left elbow and wrist joints, resulting in a greater loading in the left *erector spinae*. EMG activities for right erector spinae of 30.5% of MVC were lower than those observed for the left during the pre-intervention, and there was a significant reduction to 14% post-intervention. It is argued that the introduction of the transfer trolley not only improved the working posture and reduced the twist and lateral bending of the spine during the manual door carry, but also reduced the level of asymmetry with both left and right *erector spinae* evenly taxed. The trolley will therefore result in a notable decrement in workplace loading when applied *in situ* and the reduction in manual carriage will result in less fatigue to the worker over the 7.5hr shift.

The placement of the car door (sub-task iii) showed no difference between left and right *erector spinae* EMG. This was expected as no major changes to the current jig and work cycle were possible post-intervention. EMG reported as a %MVC was in the range of 24.1% (pre-intervention) to 25.5% (post-intervention) during the placement sub-task. Although EMG showed no notable reduction, twisting of the spine was reduced post-intervention as a result of a request for participants to step and turn with the car door. Minor changes to the placement of the door may thus elicit a reduction in twisting in the workplace, thus highlighting the need to advise operators on the most acceptable working methods for use on the Closure Line.

PSYCHOPHYSICAL RESPONSES

RPE and BDS ratings were collected during laboratory testing to evaluate the perceived task demands, and both Local (arms and back) and Central (cardiovascular) ratings were recorded to gain an understanding of the perceived demands placed on the musculoskeletal and cardiovascular door carriage activity.

Ratings of Perceived Exertion (RPE)

Figure 36 illustrates a steady increase in Central RPE, with both pre- and post-intervention responses showing a significant difference between initial (min2) and final ratings (during min8 and min10) thereby reflecting increasing perceived effort over time. Physical door carriage and an increased working pace were thus shown to have a similar incremental effect on RPE over the 10 minute testing bout.

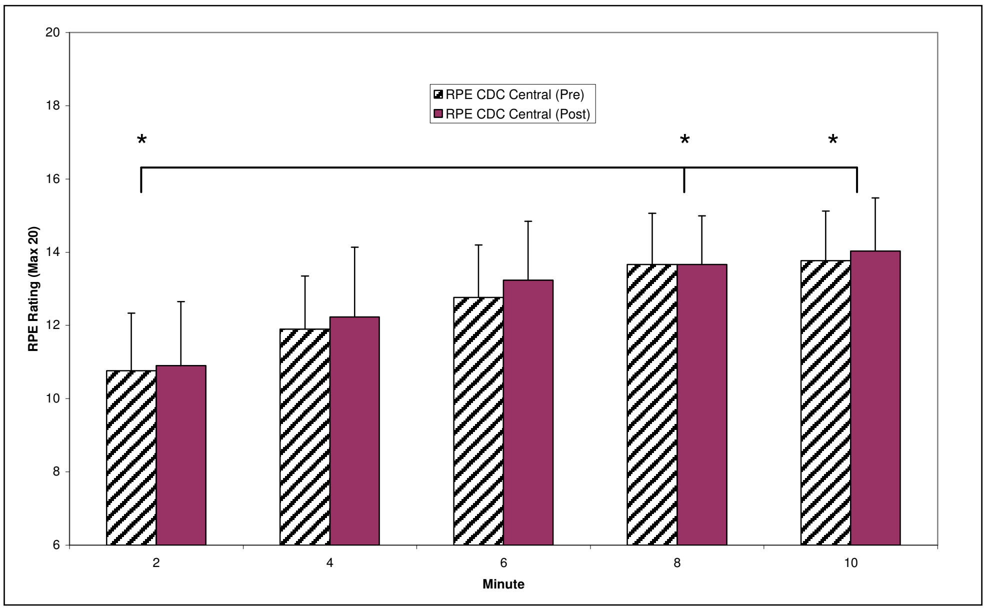


Figure 36: *Central RPE ratings for laboratory participants during the CDC. (n=30)*

** denotes significant difference (p≤0.05) between Central RPE.*

No differences were observed between manual door carriage and the trolley intervention despite the increase in pace and heart rate, indicating that participants clearly did not perceive the need to walk faster as they pushed the trolley to be more taxing than carrying the door. In fact the participants commented on a preference for an increase in working pace using the transfer trolley over the manual carriage of the car doors. This is of particular value to the industry, as there is a strong likelihood that the introduction of a trolley system could be used to increase the work productivity and working pace, while decreasing the overall physical demands placed on the worker thus reducing the cumulative effects of fatigue over a 7.5h working shift *in situ*.

Although the Local RPE score for the back showed no significant differences, pre- and post-intervention, the Local RPE specific to the upper limbs, shown in Figure 37, clearly illustrates a significant reduction in the perception of effort required of the upper limbs due to the participant not having to carry the door 6.5m.

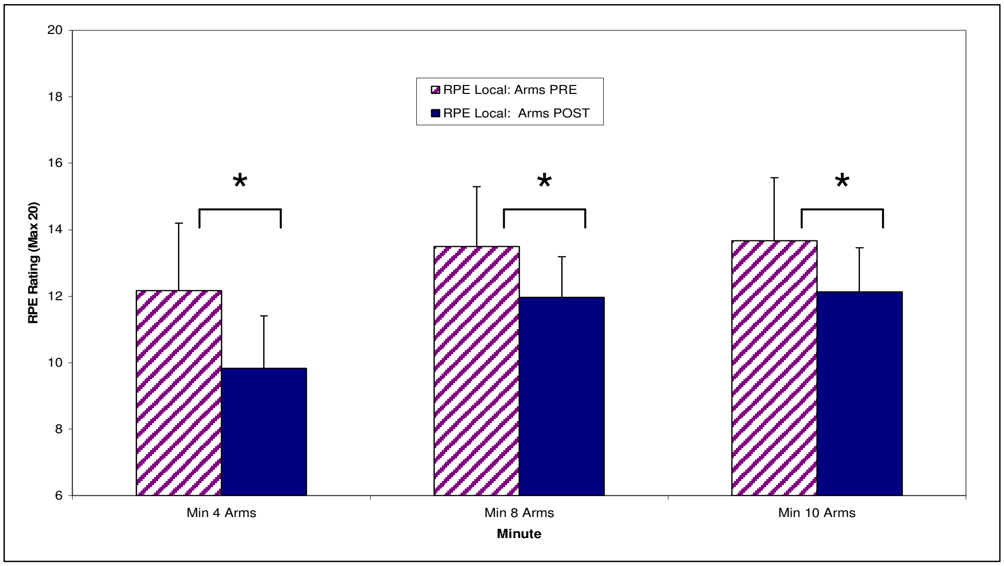


Figure 37: *Local RPE ratings for laboratory participants for the arms during the CDC. (n=30)*

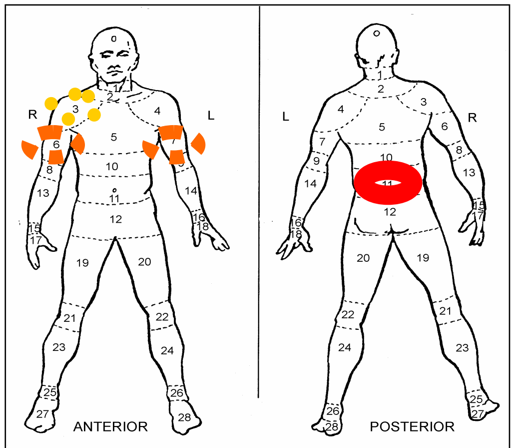
** denotes significant difference (p≤0.05) between pre- and post-intervention responses.*

Notable differences were observed between pre- and post-intervention Local RPE ratings during min 4, min 8 and min 10 (for arms). Findings in the present study concur with recent work carried out by Wang **et al.** (2000), which highlighted significant differences at the local, rather than at the central level, when considering industrial tasks.

Local RPE for the back was perceived to be 'somewhat' hard as a result of the physical effort required when lifting and placing the door, but the introduction of the transfer trolley demonstrated the benefits of the elimination of the door carry sub-task (lasting up to 10 seconds) with significantly lower RPE scores recorded for the upper extremity where the perception of effort was notably reduced post-intervention.

Body Discomfort: CDC Pre-Intervention

The BDS (Corlett and Bishop, 1976) was used to enable participants to identify the area of greatest discomfort, followed by second and third areas, and in addition they were required to rate the intensity of that discomfort on the rating scale (1 to 10).



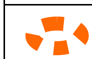
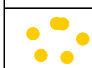
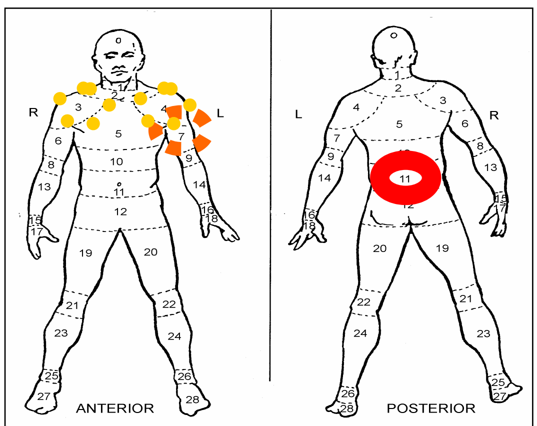
Key	Rating	Area	% of Participants Rating Discomfort in Area
	Greatest Discomfort	***11 Posterior Lower Back*** (Mean Rating: 4.8 ±1.78)	17%
	2nd area	***6 and 7 Anterior Right and Left Biceps*** (Mean Rating: 4.2 ±1.62)	23%
	3rd area	***3 Anterior Right Shoulder*** (Mean Rating: 3.0 ±1.58)	10%

Figure 38: *Body discomfort ratings recorded following the completion of the CDC pre-intervention (Condition A).*

Similar to the responses for the PTT task, the CDC ratings of body discomfort both pre- and post-intervention were highest for the lower back region, with a pre-intervention mean rating of 4.8 (±1.78). In addition the mean ratings for the second and third areas are presented in Figure 38. As the working posture adopted to lift the door from the bin requires extensive upper extremity activity in order to lift the load, the right and left biceps were the regarded as being the areas experiencing the second greatest discomfort. The right shoulder was also rated as an area experiencing discomfort due to the lifting action with the right arm elevated to carry and place the door, and follow a similar trend to Straker **et al.** (1997), who demonstrated that discomfort ratings were significantly higher for tasks that required the operator to adopt an awkward working posture.

Body Discomfort: CDC Post-Intervention

Although there were minor modifications to the lifting action, the greatest change was in the elimination of carrying the door. While the lower back discomfort was still the highest rated area of discomfort (mean: 4.7 ± 0.52), other reported areas of discomfort are highlighted in Figure 39, which illustrates that the additional areas identified were the right bicep, right and left shoulders. The participants thus experienced some discomfort during the lifting operation.



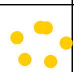
Key	*Rating*	*Area*	*% of Participants Rating Discomfort in Area*
	Greatest Discomfort	***11 Posterior*** ***Lower Back*** (Mean Rating: 4.7 ± 0.52)	20%
	2nd area	***7 Anterior*** ***Left Bicep*** (Mean Rating: 4.6 ± 1.21)	27%
	3rd area	***3 and 4 Anterior*** ***Right and Left Shoulder*** (Mean Rating: 4.0 ± 1.41)	7%

Figure 39: *Body discomfort ratings recorded following the completion of the CDC post-intervention (Condition B).*

Although the ratings of discomfort were only moderate in the laboratory, care should be taken if extrapolating these results of 10 minutes of laboratory work to a 7.5h shift. As

Corlett (1990) reported, heavy physical work will increase the levels of body discomfort experienced, and based on detailed observation of working practices (James, 2002c; James and Scott, 2006), existing rest schedules used in the automotive sector may not be sufficient to allow adequate recovery from mild to extreme body discomfort associated with poor working postures and sub-optimal task design. In such cases Corlett (1990) suggested that recovery from static work is usually slow and may in all likelihood not be achieved in a short rest break. It remains critical for each plant using intervention strategies based on sound ergonomics principles to assess the current task demands and to be guided by objective measured spinal kinematics, and the subjective discomfort responses of the workforce.

SUMMARY

Task 2: Car Door Carriage (CDC) Bodyshop Simulation

The CDC simulation consisted of three distinct sub-tasks, namely the lift, carry and placement of the door. The lift (sub-task i) was adjusted with a reduction of the height to step in and out of the bin. A minor change to the door storage height and removal of the side of the crate reduced the sagittal flexion in the spine and assisted in reducing the twist required to step out of the storage bin. In the Bodyshop area, the door carriage was identified as a high risk task, hence a transfer trolley device was built in-house and piloted using the two-door framework. A number of factors were taken into consideration when designing the transfer trolley. In accordance with the guidelines set by Jung **et al.** (2005), the requirements of the task, the working environment, operator preferences, design considerations and usability of the trolley were all taken into account in the present study. It may be argued that the post-intervention CDC sub-tasks were more suitable for a number of reasons, but most importantly because of the change from an asymmetrical door carry to a symmetrical trolley push that they elicited, for as Bridger (2003) suggested, workplace changes incorporating manual handling devices may decrease musculoskeletal strain and the physiological cost of walking by reducing the load placed on the muscles of the upper and lower extremities.

The benefits of the intervention strategies included a reduction in musculoskeletal stress achieved through a reduction in sagittal ROM, reduction in twisting position and decrease in lateral, sagittal and twisting velocities. Physiologically the responses of the participants also indicated lower levels of muscular loading with significant decrements in averaged EMG activity as a %MVC post-intervention for left and right *erector spinae*. Heart rate responses were not lower post-intervention as a result of the maintenance of the 30s work cycle, but are expected to be reduced *in situ* with the introduction of a two or four-door trolley. Perceived exertion indicated a reduction in ratings at a Local rather than at a Central level. The introduction of the trolley was deemed to reduce the loading of the arms, particularly during sub-task ii, with participants unanimously preferring the trolley to the manual door carriage in the laboratory. However, based on perceptual findings, the loading of the lower back remains an area that requires further consideration, as RPE scores and body discomfort ratings were not significantly lower post-intervention. It is clear that participants still consider the physical lifting and placement of the door to be demanding sub-tasks.

ESTIMATION OF PRACTICAL WORKPLACE BENEFITS

Findings from the present study revealed that statistically significant changes were achieved with minor alterations in working methods proposed for automotive Paintshop and Bodyshop tasks. While the changes in post-intervention responses of participants in the laboratory were small, but effective, when considering that data was only collected over a 10 minute testing bout, it is argued that the proposed interventions have great potential for reducing the cumulative loads placed on the workers' musculoskeletal and cardiovascular systems due to the improved balanced and upright working posture and the reduction in the pace of work.

In an attempt to quantify the potential workplace benefits of the proposed basic ergonomics interventions over time, two diagrammatic assessments have been conceptualised. The assumptions for the potential benefit analyses for the PTT and CDC were based upon the following: a 7.5h shift; a five-day production week; and a minimum of 48 production weeks per annum. In addition, the PTT benefit analysis assumes that the Paintshop worker completes the push-pull transfer of 70 units per shift with a minimum of two pushing or pulling actions for each sub-task for a total output of 20kg.f. The current force output required of each worker in the Paintshop amounts to 2 000kg.f over a skid transfer distance of approximately 1km per shift. Figure 40 shows the potential benefits of the PTT intervention applied to the push-pull task.

Potential ergonomics intervention benefits - PTT

Potential reductions in push-pull effort required by a worker based on measured average force output of 20kg.f (reported in kg.f)	70 units transferred per 7.5h shift in the Paintshop (0.5h break, 10 vehicles moved per hour)	Potential reductions in movement required of a worker based on measured average push-pull distance of 10m (reported in km)
20	Per push-pull task	0.01
200	Per hour	0.1
2 000	Per shift	1
10 000	Per week	5
40 000	Per month	20
400 000	Per annum	240

Figure 40: *PTT intervention analysis based on push-pull force and distance measurements.*

The proposed reduction in asymmetrical one- and two-handed pushing and pulling activities in the Paintshop will reduce cumulative joint loading by 480 000kg.f and decrease the movement distance and associated energy cost of these potentially hazardous tasks by 240km per worker per annum.

The potential benefits of the basic CDC trolley intervention are no less pronounced than for the PTT. CDC laboratory findings support the proposed introduction of the trolley with significant changes recorded post-intervention with the transfer unit eliminating the asymmetrical working posture during manual door carriage, reducing the stresses on the musculoskeletal system, and notably reducing the perception of effort specific to the upper limbs.

The CDC benefits analysis utilises the door mass (21kg) and the recorded distance of carriage (6.5m) from the GM Bodyshop Closure Line. Figure 41 reveals that the provision of a door transfer trolley will assist in eliminating the manual carriage of 1.47t over an estimated distance of 0.46km per shift per worker (based on 70 doors lifted per 7.5h shift).

Potential ergonomics intervention benefits - CDC Trolley

Potential reductions in manual door carriage by a worker based on the carriage of a 21kg car door (reported in tonnes)	70 doors lifted per 7.5h shift (0.5h break, 10 doors lifted per hour)	Potential reductions in distance moved by a worker based on measured distance of carriage of 6.5m (reported in km)
0.021	Per door carriage task	0.0065
0.21	Per hour	0.065
1.47	Per shift	0.46
7.35	Per week	2.275
29.4	Per month	9.1
352.8	Per annum	109.2

Figure 41: *CDC intervention analysis based on car door mass and carriage distance measurements.*

The provision of a door transfer trolley on the Closure Line will eliminate 352.8t of manual door carriage over a distance of 109.2km per annum per worker. Extrapolation of these benefits from one worker to all 12 operators currently completing the manual handling of vehicle parts in the Bodyshop will result in a cumulative reduction of 4 233.6t over 1 310.4km eliminated per year.

The findings from the present study are specific to push-pull and door carriage tasks in the GM Paintshop and Bodyshop, where the benefits of successful ergonomics intervention are pronounced. It is argued that if minor changes in two specific work areas are able to reduce musculoskeletal stresses, physiological cost and potential hazards with "low-cost" interventions, that changes in working practices aimed at the minimisation of asymmetrical push-pull activities and manual work across all seven South African automotive plants have great potential to reduce the incidence of WMSDs for the entire industry on an annual basis. As Sen (1984), Scott (1996; 1997) and

Kogi **et al.** (1998) have argued, the application of small workplace changes in IDCs have the potential to make a profound impact in the workplace.

FIELD RE-EVALUATION RESULTS

Re-evaluation of Field Task 1: Paintshop Area

The Paintshop at the GM Struandale plant has been extensively modified following the suggested interventions, which were based on the rationale of Shoaf **et al.** (2000), who argued that the main guiding principle to improving human work performance should be to balance the task demands with the capabilities of the human operator. Figure 42 demonstrates the redesigned working area in the Paintshop with the operator riding on the transfer unit. Manual transfer trolleys have been removed from the Paintshop area resulting in an elimination of most sub-optimal working practices in this area. A further change that has assisted in the change process has been the automation of the roller bed systems, which have been a long-term concern in the GM Paintshop.

Figure 42: *Automated transfer trolley used in the Paintshop post-intervention.*

Reassessments were conducted on three workers in this area (mean age 34yr ±10.84). Operators interviewed during the re-evaluation unanimously preferred the automated units to the manual transfer trolleys, where the predominant reason given for the preference was the elimination of the manual one and two-handed pulling actions which were used pre-intervention.

Time-motion observations were conducted in order to assess the work requirements and these demonstrated that only occasional pushing at the front of the unit was required in the rare instances when the roller beds were not moving the vehicle unit as required. The estimated work cycle time was recorded as 35s, demonstrating a notable reduction in duration and pace of work in this area (50s pre-intervention).

Working Posture

In contrast to the pre-intervention observations where the work demands were excessive, and working postures were poor and potentially hazardous, the post-intervention observation clearly demonstrated the benefits of effective ergonomics intervention in the workplace by eliminating awkward postures and improving conditions in the Paintshop.

Re-evaluation of Field Task 2: Bodyshop (Closure Line) Area

The work tasks required in the Bodyshop area proved to be more difficult to alter given the confined space on the Closure Line and the supply of the doors in a specific storage bin from an international supplier. The proposed trolley is still under consideration, with potential design changes mooted for the transfer unit to incorporate the door carriage while minimising the likelihood of damage to the doors on the Closure Line. However, a notable change on the Closure Line has come in the form of job rotation, which not only reduced musculoskeletal stresses, but also decreased the pace of work. The four workers (mean age 31.8yr ±5.62) interviewed in the Bodyshop noted that the implementation of an effective job rotation cycle had reduced their physical loading and resulted in lower levels of discomfort at the end of the 7.5h shift.

Working Posture

Following the provision of proposed interventions, the GM "Ergonomics Facilitation Team" discussed the potential solutions and evaluated the feasibility of each recommendation. A number of changes have subsequently been made in the Bodyshop, which have resulted in less demanding job requirements. Most notably the step into the bin (see Figure 43a) has been reduced through the provision of a low-cost step (300mm) in an attempt to minimise the likelihood of tripping while lifting the door out. Workers have also been educated in appropriate lifting techniques, which have resulted in a major reduction in the twisting action while carrying the door from the bin to the welding jig. The placement of the bins further back from the line has allowed more space for carriage of the door. Furthermore, the distance of carriage has been significantly reduced from 6.5m to approximately 2.5m in the Bodyshop. This logistical change in the distance of carriage along with the implementation of job rotation, has made a notable difference to operator perceptions of work demands, where the workers interviewed remarked that the changes had reduced the overall levels of discomfort experienced.

a **b** **c**

Figure 43 a, b and c: *Reduced "step-in" (a), symmetrical lifting (b) and reduced "step-out" (c) of the bin in the Bodyshop post-intervention.*

Figure 43b demonstrates that the vertical placement of the doors in the storage bin results in a more balanced manipulation of the door and less stooped lifting, as was the case in the pre-intervention observations. The step out of the bin is now a controlled movement, which reduces the chance of slipping or falling off the modified step. Non-slip material has been used to construct the step platform, which also reduces the potential problems associated with wet safety footwear.

FIELD RE-EVALUATION PHYSIOLOGICAL VARIABLES

Heart Rate Responses

Workplace MMH tasks place the operator under differential physiological strain during the working shift. In general the re-evaluation of heart rate responses in both areas demonstrated reductions in recordings pre- versus post-intervention, while the intervention of automation in the Paintshop resulted in a significant reduction in heart rate recordings in this area of the plant. Heart rates ranged from 80 to 115 $bt.min^{-1}$ in the Paintshop pre-intervention, and between 75 and 90 $bt.min^{-1}$ post-intervention. Automation of the trolley system has significantly reduced the physiological loading of the operator with a reduction in the mean heart rate response from 94 (±9.77) $bt.min^{-1}$ to 81 (±3.72) $bt.min^{-1}$ post-intervention. In addition, harmful working postures such as the one-handed pulling have been eliminated, creating a major improvement in working postures, thus minimising the chances of musculoskeletal stress.

Changes in physiological responses in the Bodyshop were not as pronounced as those in the Paintshop. Mean heart rate responses recorded were not significantly reduced on the Closure Line (mean 90 $bt.min^{-1}$ pre-intervention and mean 88 $bt.min^{-1}$ post-intervention), as the work pace was similar pre- versus post-intervention. However, the benefits specific to this area were more particularly noted in the areas of postural analysis, where much of the bending and twisting had been eliminated, thus reducing the likelihood of musculoskeletal injuries, and once the door trolley is introduced it is anticipated that the working pace will decrease and stresses on the cardiovascular system will be reduced.

FIELD RE-EVALUATION PSYCHOPHYSICAL RESPONSES

Ratings of Perceived Exertion (RPE)

Perceived exertion ratings were collected every 30min during the re-evaluation in the field. Table XVI highlights the mean Central and Local RPE ratings recorded pre- versus post-intervention at selected time intervals in the GM Struandale plant.

Table XVI: *Changes in RPE pre- versus post-intervention in the Paintshop area.*

	Central RPE				Local RPE (Arms and Back)			
	Min30	**Min60**	**Min90**	**Min120**	**Min30**	**Min60**	**Min90**	**Min120**
Pre-Intervention	11.0 (1.22)	11.6 (1.14)	11.0 (1.10)	11.0 (1.26)	12.2 (3.27)	13.0 (2.45)	12.3 (2.45)	13.0 (1.67)
Post-Intervention	7.3 * (0.56)	8.0 * (1.00)	8.7 * (0.58)	8.8 * (0.58)	7.7 * (0.58)	7.7 * (0.58)	8.0 * (1.00)	8.3 * (0.58)

(Means with standard deviations in brackets, shaded area post-intervention)
* *denotes significant difference ($p \leq 0.05$) between pre- and post-intervention responses.*

Analyses of RPE ratings showed a significant reduction in Central and Local ratings pre- versus post-intervention during all periods. The substantial changes in working methods resulted in the workers evaluated in the Paintshop rating the tasks as “very light” given the use of the automated ride-on trolley in this section of the plant. Whereas the arms and back were rated “somewhat hard” pre-intervention, the post-intervention ratings are “light” due to the elimination of the “worst-case” pushing and pulling in this area.

Despite there being no difference in heart rate findings in the Bodyshop, their perception of effort showed a nominal reduction in Central ratings, and a significant drop in the perception of exertion in the upper limbs and back, as shown in Table XVII.

Table XVII: *Changes in RPE pre- versus post-intervention in the Bodyshop area.*

	Central RPE				Local RPE (Arms and Back)			
	Min30	**Min60**	**Min90**	**Min120**	**Min30**	**Min60**	**Min90**	**Min120**
Pre-Intervention	11.0 (1.90)	12.3 (2.34)	12.8 (2.56)	12.7 (2.58)	11.3 (1.63)	13.3 (2.63)	12.8 (2.56)	12.8 (2.56)
Post-Intervention	10.7 (1.71)	11.0 (1.63)	11.5 (1.00)	11.8 (1.89)	9.5 * (2.78)	9.75 * (2.77)	10.5 * (3.26)	11.3 * (3.28)

(Means with standard deviations in brackets, shaded area post-intervention)
* *denotes significant difference ($p \leq 0.05$) between pre- and post-intervention responses.*

This finding may be explained by the reduction in carriage distances and the introduction of job rotation in the Bodyshop post-intervention.

Body Discomfort Map and Rating Scale

The area most frequently rated post-intervention was once again the lower back (region 11) on the BDS in both areas of the plant. Ratings of body discomfort by Paintshop and Bodyshop workers confirmed a notable reduction in operator perception of intensity of discomfort from 5.5 (± 1.93) on the 10-point rating scale of the BDS during the first hour which was reduced to 3.3 (± 0.76) post-intervention, and in the second hour from 5.8 (± 1.71) to 3.4 (± 0.79).

CHAPTER FIVE
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

INTRODUCTION

The present study assessed the demands that two specific manual tasks placed on selected operators in a South African automotive plant. Work-related hazards affecting the overall efficiency of the human operator were identified and prioritised for further investigation, and were then simulated in a rigorously controlled laboratory setting. Scott and Christie (2004) reported on the benefits of laboratory research, but cautioned that practical application of interventions is the key to ensuring that improvements are experienced within the specific workplace. In this situation the focus was on an international automotive industry in South Africa, a country which is recognised as a developing region. The findings of this study are thus best considered within the scope of IDC industry, where simple, “low-cost” solutions are vital to improving working conditions for the indigenous workforce.

The South African automotive industry exhibits a combination of simple and advanced working methods (James, 2002a; James and Todd, 2003; James and Scott, 2006). The consequence is that interventions based on “low-cost” changes are highly specific to selected manual work areas. The changes proposed were shown to be essential in the case of the GM automotive plant, in which small modifications were able to elicit substantial improvements in operator safety and overall work productivity.

Furthermore, an increasing awareness of basic ergonomic knowledge and the establishment of an “Ergonomics Facilitation Team” were desired outcomes of this research, as little or no understanding of ergonomics have previously been reported in the automotive industry (James, 2002b, Khumalo, 2004; Visser, 2004). Basic training and awareness sessions were considered essential at a number of original equipment manufacturers in South Africa.

SUMMARY OF PROCEDURES

A "field-laboratory-field" approach was utilised in the present study. Sub-tasks were selected in the automotive plant based on "worst-case" prioritisation. The field push-pull evaluation aimed to assess the forces required to complete a series of sub-tasks used in the moving of vehicle frames in the automotive Paintshop. *In situ* analyses were conducted on a sample of six Paintshop operators to assess temporal factors of the task, as well as basic biophysical, physiological and perceptual responses of the workers. The forces required to move skid units onto a trolley-based platform, and then onto a roller-based conveyor line were quantified. Push-pull forces were collected using a Chatillon™ Hand Held Dynamometer. Heart rate responses were recorded using Polar™ monitors, activity counts with the RT3 tri-axial accelerometer, and perceptual responses using Borg's Ratings of Perceived Exertion (RPE) and Corlett and Bishop's Body Discomfort Map and Rating Scale (BDS) following a standardised protocol.

The Bodyshop evaluation assessed the car door lift, carry and placement sub-tasks completed by six Closure Line workers. Additional sub-tasks in this area were completed with the assistance of mechanical hoisting devices. The primary concerns relating to the current Bodyshop tasks were identified as follows: the step up and into the storage bin to collect the door and then stepping down and out of the bin; the sharpness of the metal edges of the doors; the space confinement placed on operators due to the protective curtains and overhead jigs in the Bodyshop Closure Line; and the physical load carriage requirements of completing a working shift carrying front doors with a mass of 21kg.

Following the field assessment, laboratory experimentation of the selected industrial working operations was conducted for Task 1 – Paintshop Trolley Transfer (PTT) and Task 2 – Car Door Carriage (CDC), with Condition A simulating the existing industrial scenario (pre-intervention) and Condition B (post-intervention) conducted to assess the effect of the basic ergonomics interventions proposed. The laboratory cohort consisted of 30 student participants with no history of manual work experience. Although no medical examination was deemed necessary, the participants claimed to be free of injury or illness on the days of testing in the laboratory. Testing was conducted on two separate days for each of the laboratory conditions.

A field re-evaluation was conducted in the Paintshop and Bodyshop areas as per the initial field investigation. The selected workplace changes adopted by the automotive industry were assessed in an attempt to quantify the reduction in risk (evaluated by means of follow-up work observations, time-motion analyses, monitoring of heart rate responses and recording of perceptual responses). The recently installed automated ride-on transfer trolleys (Paintshop) and work organisational changes (Bodyshop) were evaluated in the follow-up phase.

SUMMARY OF RESULTS

Evaluation of Field Tasks

The original workplace study included detailed job analyses in two areas of the GM plant. The largest unit manually moved in the Paintshop, vehicle Model C, was shown to be considerably heavier than the other units evaluated, and force outputs were considerably higher when moving Model C on the skid. Peak initial forces ranged from 18.2 to 21.7kg.f for the one-handed pull, and values for the two-handed pull ranged from 20.1 to 23.6kg.f. A similar range of values was recorded for the pushing tasks with the one-handed push range being 20.5 to 22.0kg.f and the two-handed push range being 17.9 to 22.3kg.f. Poor workplace design and large awkwardly shaped vehicle frames, coupled with high force requirements in many of the pulling and pushing tasks resulted in the operators needing to adopt extremely awkward working postures.

Similar analysis of Bodyshop working postures demonstrated that the installation of doors required a hazardous step into the storage bin, and furthermore the carriage of the door forced the operator in a twisted position when moving to the jig for final placement.

Heart rate responses were recorded for two hours while the workers went about their repetitive jobs. The average working heart rates recorded during the initial fieldwork observation were higher at 94 $bt.min^{-1}$ (±9.77) for the Paintshop workers, than the 90 $bt.min^{-1}$ (±13.98) recorded for the Bodyshop workers. Heart rates recorded ranged from 80 to 115 $bt.min^{-1}$ in the Paintshop, with a greater range and higher maximum (70 and 124 $bt.min^{-1}$) in the Bodyshop area.

Energy expenditure predictions calculated for the tasks in the Paintshop (5 527.3kJ.shift) were statistically higher than those of the workers in the Bodyshop area (4 822.0kJ.shift). It should be noted that activities in the Bodyshop are predominantly self-paced, and in addition the Closure Line is occasionally subject to production down-time or vehicle backlogs, hence the operators are able to take more informal rest breaks. These lower activity levels are also reflected in the lower mean working heart rates recorded in the Bodyshop. However, despite the lower physiological costs, the workers perceived the door carry to be more demanding than in the case of completing the trolley push-pull tasks. Significant differences in Central RPE were observed for most of the two hours, and were only higher for Paintshop workers towards the end of the shift. The greatest body discomfort reported by both groups was in the lower back region, with a moderate intensity of 5.5 to 5.8 over the two hours of data collection.

Laboratory Simulation

Task 1: Paintshop Trolley Transfer (PTT)

PTT laboratory experimentation confirmed that the existing working posture used for two-handed pulling increases the risk of slips and falls, primarily as a result of the centre of mass being outside the base of support, and in the longer term, work-related upper limb disorders. In contrast, the method proposed with a simple change to the pulling attachment (in the form of a lengthened rope) eliminated a significant amount of risk. The mean lean angle recorded from the vertical position for the two-handed pre-intervention pulling was 23.7° (±3.51), which was reduced to 13.9° (±2.21) post-intervention. Although the lengthening of the pulling rope did significantly reduce the angle of lean, an alternative method was proposed by the company, namely that the transfer trolleys could be automated to eliminate the awkward working postures and the need to walk backwards altogether.

Spinal kinematic responses showed a significant reduction in average twisting velocity between the one-handed and two-handed pulling post-intervention due to the improved symmetry of the two-handed pulling method. Participants preferred the intervention to the current two-handed pull observed *in situ* as it provided a more comfortable working posture and eliminated the excessive lean during the skid pulling. In addition the maximal backward lean was significantly reduced as a result of the adapted pulling style, and maximum lateral velocity decreased from one-handed to two-handed pulling. It was evident that the operators had better control over the skid unit as they were able to work with a balanced posture and did not require additional effort to maintain balance with the simulated load moving in their direction, thus supporting the argument of De Looze **et al.** (2000), who proposed that force output and maintenance of stability is dependent on the direction of the pushing or pulling effort.

Predicted average probabilities of low back disorder risk using the OSU Risk Model were calculated for pre- and post-intervention pushing and pulling. Highest LBD risks were 36.8% (±8.03) for one-handed pulling and 38.2% (±4.03) for the one-handed push. The risk of low back problems was significantly reduced during the interventions to the two-handed pull (21.7% ±5.31) and the two-handed push (21.9% ±4.53). Statistical analyses also showed a significant reduction between one-handed pulling and pushing, and the proposed two-handed pulling and pushing interventions.

The highest mean working heart rate (103 $bt.min^{-1}$ ±11.62) was recorded for the two-handed asymmetrical push. The pushing posture during this trial was awkward and particularly uncomfortable, with the left hand raised above the right hand to replicate the pushing action observed in the field. A notable decrement in heart rate response to 93 $bt.min^{-1}$ (±11.77) was recorded during the symmetrical two-handed pushing intervention. A statistically significant reduction was also observed between the one-handed and two-handed push data when compared to the proposed intervention strategy. Participants were clearly less taxed during the two-handed pushing intervention, and a subjective preference for this method of task completion was also reported by the laboratory participants.

Highest averaged EMG activity data was recorded during the two-handed pushing trials specifically for the left and right *medial deltoids* (mean 148.1 and 126.4μV respectively) due to the asymmetrical posture adopted by the participant, which in turn led to a significantly lower level of right *erector spinae* EMG (38.9μV). While the positioning of the left hand above the right in these trials resulted in reduced back muscle loading on the right hand side, it noticeably increased the loading on the left and right *medial deltoid* region. The introduction of symmetrical two-handed pushing resulted in a balanced distribution of the muscular activity between the left and right hand *medial deltoids* and *erector spinae* (reduced to a mean of 55.3 and 58.4µV from 148.1 and 126.4μV in the *medial deltoids*).

Pre-intervention PTT tasks were asymmetrical and demonstrated the effects of an awkward working posture, twisted and bent spine, uneven joint, muscle and cardiovascular loading and an overall lack of subject stability. The change to a symmetrical working posture elicited a notable improvement in stability, even distribution of the load between the left and right hand sides of the musculoskeletal system, and reduced the spinal and cardiovascular load post-intervention.

Task 2: Car Door Carriage (CDC) Bodyshop

CDC experimentation (Task 2) demonstrated that the storage of the car door in the bin necessitated an average level of sagittal flexion of 28.0° (±4.78) for the pre-intervention lift. Minor changes in the storage height of the door resulted in a significant reduction in sagittal flexion post-intervention to 20.7° (±5.65). The lifting style utilised noticeably influenced the level of sagittal flexion during the CDC lift (sub-task i). A range of 16.8° to 36.7° was observed for the pre-intervention phase, depending largely on whether a 'stoop', 'semi-squat' or 'squat' lift was chosen as the preferred lifting style. This range was subsequently reduced under Condition B where no 'squat' lifts were observed.

Post-intervention lifting was modified to eliminate the excessive step into and out of the industrial storage bin. The risk of tripping while stepping into, and falling while stepping out of the bin were minimised during the post-intervention lifting phase.

Predictions of average probability of LBD risk were 50.3% (±5.91) for pre-intervention and 39.8% (±5.10) for post-intervention lifting. Simple changes in the current working requirements and posture thus resulted in a reduction of the probability of lower spinal problems to 10.5% in the post-intervention phase.

Analyses of EMG responses showed a significant reduction between pre- and post-intervention levels of mean *erector spinae* activity as a percentage of MVC for the combined lift, carry and placement of the door. The greatest reduction was associated with the introduction of the transfer trolley for the carriage phase of the CDC (sub-task ii) where statistically significant differences were observed between left and right *erector spinae* EMG as a %MVC pre- versus post-intervention (EMG as a %MVC reduced from 35.1 to 13.7% and 30.5 to 13.9% for left and right *erector spinae* respectively). No statistical differences in EMG activity (%MVC) were apparent during the car door lift from the simulated storage bin or during the final placement of the car door. Both of these sub-tasks retained the same fundamental requirements, namely a lift of a 21kg front door (sub-task i) and placement of the vehicle part on a simulated jig (sub-task iii).

The provision of the trolley was perceived to be of significant benefit to the participants in the laboratory experimentation. Reduced body discomfort ratings under Condition B suggested that there was adequate corroboration to propose that interventions should be applied in the field.

Re-evaluation of Field Tasks

The field re-evaluation was conducted in the modified Paintshop and Bodyshop areas at the GM Struandale plant. The most notable change in the GM workplace has been the implementation of automated ride-on trolleys in the Paintshop. Workers interviewed during the re-evaluation collectively preferred the automated units to the manual transfer trolleys due to the elimination of the manual pulling and pushing actions. The workplace changes implemented have substantially reduced the postural stresses placed on the workforce and reduced the risk of MSI to the Paintshop workers.

Changes in the Bodyshop area have been more difficult to implement due to workplace logistics. Four workers were observed on the Closure Line. The step into the bin has been significantly reduced and job rotation has been more tightly controlled in an effort to reduce the musculoskeletal loading of the operators. Workers now alternate the door lifting operation, and revised rest break schedules are deemed to be beneficial by the staff interviewed. GM Struandale engineering personnel are presently working on a four-door transfer trolley, which will minimise physical load carriage and reduce the pace of work in the Bodyshop.

Heart rate recordings ranged from 80 to 115 $bt.min^{-1}$ in the Paintshop pre-intervention, and between 75 and 90 $bt.min^{-1}$ post-intervention, indicating a significant difference between the pre- and post-intervention 'working' heart rate responses during all collection periods. The musculoskeletal demands were similar pre- versus post-intervention in the Bodyshop Closure Line and no notable decrement in heart rate responses was noted. However, a reduction in perceived exertion and body discomfort was reported.

Analyses of RPE ratings showed a significant reduction in Central and Local ratings pre- versus post-intervention during all periods in the Paintshop. Most operators rated the revised task demands as 'very light' to 'light'. Bodyshop workers rated the current task demands numerically lower for both Central and Local RPE post-intervention. Body discomfort ratings showed a mean reduction in the intensity of discomfort during the first hour from 5.5 (± 1.93) to 3.3 (± 0.76), while in the final hour discomfort intensity was reduced from 5.8 (± 1.71) to 3.4 (± 0.79) post-intervention. The area most frequently rated post-intervention was once again the lower back on the BDS (region 11).

STATISTICAL HYPOTHESES

The significant reduction in virtually all variables selected for analysis pre- versus post-intervention results in a general rejection of the null hypotheses, which are discussed in more detail.

Hypothesis 1: Spinal Kinematic Responses

The first hypothesis focused on laboratory spinal kinematic responses using the industrial Lumbar Motion Monitor.

(a) The results of the PTT (Task 1) force rejection of the null hypothesis as kinematic responses (ROM, twisting velocity and lateral velocity) decreased significantly during symmetrical post-intervention two-handed pulling and pushing respectively.

(b) The null hypothesis is rejected for spinal kinematic responses during the CDC simulations (Task 2) as findings demonstrated a significant reduction in ROM, spinal twisting and lateral velocity post-intervention.

Hypothesis 2: Physiological Responses

The second hypothesis focused on physiological responses and was sub-divided into heart rate responses (HR) and EMG activity (EMG). The null hypothesis that was tested was that there would be no change in the cardiovascular responses and muscular activity during the two experimental tasks (PTT or CDC) for each condition (pre- or post-intervention).

(a) Hypothesis 2 is rejected in the case of the PTT tasks as both HR and EMG responses were significantly reduced for two-handed pushing and pulling due to the introduction of symmetrical, controlled and balanced pushing and pulling actions post-intervention.

(b) The null hypothesis is rejected for cardiovascular responses during the CDC as HR responses showed a significant increase during the post-intervention testing, arguably due to the maintenance of the current work cycle time of 30s as observed in the Bodyshop Closure Line *in situ*. It is argued that the working heart rate will be maintained at an acceptable level in the workplace through the introduction of a two- or four-door transfer trolley, which will reduce the level of the cardiovascular load during the shift.

(c) The null hypothesis for EMG activity during the CDC is rejected due to a significant reduction in muscular loading in the post-intervention condition. EMG reported as %MVC was significantly reduced in the left and right *erector spinae* over the entire 10 minutes of experimentation. In addition statistically significant differences were observed in EMG %MVC during sub-task ii (door carry/trolley push).

Hypothesis 3: Psychophysical Responses

The final hypothesis dealt with perceptual responses to Ratings of Perceived Exertion (RPE) and Body Discomfort Rating (BD) of laboratory participants during the two laboratory tasks.

(a) The PTT demonstrated no significant differences for BD ratings pre- versus post-intervention and the null hypothesis is therefore tentatively retained.

(b) Hypothesis 3 is rejected for Local RPE ratings for the CDC where arm specific ratings showed a significant reduction in perceived effort due to the introduction of the transfer trolley. However, the null hypothesis is tentatively retained for Central RPE as no significant difference was observed.

(c) The null hypothesis is tentatively retained for BD ratings for the CDC as no statistically significant changes were observed for these psychophysical ratings.

CONCLUSIONS

It has been argued that manual tasks require considerable effort on the part of the human operator and frequently result in excessive strain of the musculoskeletal and cardiovascular systems (Dempsey, 1998). The automotive workers in the present study had been subjected to sub-optimal working operations under demanding conditions in a hot and noisy working environment. Many of the workplace tasks required awkward working postures, which placed substantial musculoskeletal stress on the operator, as well as placing them at high risk of slipping and tripping. Work rest schedules and job rotation were poorly controlled, resulting in cumulative fatigue of the workforce over the duration of the 7.5h working shift at the GM Struandale plant.

IDC industry continues to experience the need for realistic use of “low-cost, no-cost” ergonomics (Shahnavaz, 1996; Scott and Christie, 2004). The primary objective of the present study was thus to provide the automotive industry with simple interventions which would require limited expense in order to bring about notable changes in the workplace. The Paintshop interventions aimed to reduce the pulling actions, which required awkward postures on the part of the worker. Two-handed pushing from the side was changed to the front of the unit, with the worker being in a more balanced position and the load moving away from him. The automotive plant has exceeded the basic intervention proposed in this area with the provision of automated transfer units, which completely eliminated the need to push or pull the units. The workplace modifications have resulted in notably lower levels of biophysical and physiological loading, while perceptual responses of the workers *in situ* highlight a major change in their perceptions of the job.

Changes to workplace logistics were prioritised for the Bodyshop Closure Line due to the oppressive and cramped working conditions observed during the original field investigation. Interventions proposed included low-cost workplace logistical changes in the form of a door transfer trolley, revised bin storage and increasing workplace space by moving the bins and the protective curtains in this area. Changes implemented in this area included the use of a step platform for a reduction in the step in to, and out of the industrial storage bin. The bins have been moved much closer to the jigs (carriage reduced from 6.5 to 2.5m) and slightly back from the working area to allow more space for the workers carrying the door. The protective curtains have also been trimmed to allow for airflow through the Closure Line without increasing the likelihood of the welding sparks and fumes escaping to other areas of the GM plant.

In addition, job rotation was suggested to the GM staff tasked with the implementation of workplace changes. This change was considered particularly relevant in the Bodyshop where manual work still dominates. All these minor changes in working practices should make a significant contribution to reducing the physical loading of the workforce.

RECOMMENDATIONS

The application of ergonomics in an IDC such as South Africa is dependent on directed research being conducted *in situ* on manual labourers who are still required to move excessive loads while adopting awkward working postures under sub-optimal working conditions. To this end the following recommendations are made in an attempt to highlight the steps required to facilitate this process:

- Field research needs to be conducted on a variety of manual labourers in IDCs within their actual working environments. Responses need to encompass a holistic assessment of biophysical, physiological and perceptual measures, as workers need to be assessed rather than data collected on a student cohort with limited experience in manual activities, for as Scott and Renz (2006) suggested, responses of a student sample differ considerably to a sample of work-hardened manual handlers.

- Additional laboratory simulations of high risk automotive manual handling tasks are proposed. Detailed analysis of EMG responses specific to automotive jobs would facilitate a greater understanding of muscle recruitment patterns and activity levels, specifically in the upper limbs and lower back.

- The South African automotive industry, given the resources available, needs to be far more proactive in the application of ergonomics planning and interventions in the workplace. Manufacturing plants need to be tasked with the establishment of ergonomics working groups or 'facilitation teams', who must provide detailed input during preparation and implementation of any workplace improvements or changes.

- Given the size of each automotive plant it is not unrealistic to suggest that an ergonomist should be appointed to oversee workplace interventions and assist in the workplace organisation for each production concern in South Africa. Trained ergonomists are part of the multi-disciplinary teams of all multinational automotive organisations and the same appointments need to be made in advancing IDC industries.

- The changes proposed in the present study have focused primarily on the micro-ergonomics approach; however, the automotive industry has potential to be far more proactive in the application of basic interventions based on ergonomics principles in the workplace. The utility of a macro-micro approach (Scott **et al.**, 2003) is thus proposed for the automotive industry, which has great potential to be the forerunner in the utilisation of **applied** ergonomics in South Africa. Examples of changes to these two tasks could be used as examples for other work areas where manual labour still predominates.

- To augment the process, the automotive plants in South Africa need to more precisely document 'best practices' and quantify the cost-benefit accounting of ergonomics interventions applied in the workplace. With this approach the automotive industry will continue to lead the growth in the South African manufacturing sector.

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APPENDICES

Appendix A: General Information

Informed Consent Form

Letter of Information

Informed Consent Form

Department of Human Kinetics and Ergonomics
SUBJECT CONSENT FORM

I, ______________________________ , having been fully informed of the research entitled:

Field and Laboratory Analyses of Manual Tasks
in the South African Automotive Industry
(Jonathan P. James)

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.

____

(PRINT NAME) SUBJECT (SIGNED) (DATE)

____

(PRINT NAME)
PERSON ADMINISTERING INFORMED CONSENT (SIGNED) (DATE)

____

(PRINT NAME) WITNESS (SIGNED) (DATE)

Letter of Information

FIELD AND LABORATORY ANALYSES OF MANUAL TASKS IN THE SOUTH AFRICAN AUTOMOTIVE INDUSTRY (Jonathan P James)

Dear Potential Participant

Thank you for volunteering to be a participant in this PhD Research Project. You will be part of a group who will have a number of basic measurements taken during working shifts in the Paintshop or Closure Line.

The testing will take place in the GM Struandale Plant and will be supervised by a senior academic. You will be required to perform your usual working tasks as normally as possible, including taking breaks if you so wish. The testing session will involve the collection of the following data: age, years of experience, stature, body mass, shoulder height, leg length, wrist height, left and right grip strength and back strength. In order to assess the physical demands of your working tasks you will be required to wear a heart rate monitor and accelerometer for two hours of your standard working shift. In order to get a better understanding of your perceptions of work demands we will also be using a rating of perceived exertion (RPE) scale and body discomfort scale. You will be asked to rate how hard you feel your heart and your muscles are working at 15 minute intervals during the working shift. We will be asking you to identify any body discomfort after the end of the 1st and 2nd hours of testing.

The research team will be making use of video and digital camera equipment to record some of the sub-tasks in your area. None of this material will be made available for public viewing, but will be used to see exactly how the job is done so that we can repeat the action in the laboratory for research purposes. Your anonymity will be guaranteed in the use of all video and photographic material.

You are free to stop or leave the study at any time, should you wish. No financial remuneration will be provided for participation in this study.

Jonathan James (PhD Student)

Appendix B: Data Collection

Participant Data Sheets

Work Observation Sheets

Field Investigation (GM)

Demographic and Anthropometric Data

Participant Code:	
Name (Record Purposes Only):	
Age:	
Years of Experience:	
Stature (mm):	
Body Mass (kg):	
Acromiale Height (mm):	
Stylion Height (mm):	
Trochanteric Height (mm):	

Strength Data

Grip and Back Strength

Measure:	**Trial 1**	**Trial 2**
Grip: Right		
Grip: Left		
Back		

Participant Data Sheets: Laboratory Investigation

Demographic and Anthropometric Data

Participant Code:	
Name (Record Purposes Only):	
Age:	
Years of Experience:	
Stature (mm):	
Body Mass (kg):	
Acromiale Height (mm):	
Stylion Height (mm):	
Trochanteric Height (mm):	
Body Fat %:	

Strength Data

Grip and Back Strength

Measure:	Trial 1	Trial 2	Trial 3
Grip: Right			
Grip: Left			
Back			

Pushing and Pulling Strength

Measure:	Trial 1 Peak	Trial 1 Mean	Trial 2 Peak	Trial 2 Mean
Push				
Pull				

Work Observation Sheets

GM Struandale TASK OBSERVATION

Area: Paintshop

Worker Code:	

Task Description:

Unit Moved:	
Unit Moved:	
Unit Moved:	

Sub-task Identified:

Push: Single Hand	**Push:** Double Hand	**Pull:** Single Hand	**Pull:** Double Hand	Trolley ride on
Estimated Time:	Estimated Time:	Estimated Time:	Estimated Time:	Estimated Time:

Overall Work Cycle Time:

General Comments (Any obstructions or ST&F hazards):

WORKER RESPONSES

Heart Rate Responses:

15 minutes	30 minutes	45 minutes	60 minutes	75 minutes	90 minutes	105 minutes	120 minutes

Comments on additional heart rate recordings:

RPE:

Central (Cardiovascular)

15 minutes	30 minutes	45 minutes	60 minutes	75 minutes	90 minutes	105 minutes	120 minutes

Local (Musculoskeletal)

15 minutes	30 minutes	45 minutes	60 minutes	75 minutes	90 minutes	105 minutes	120 minutes

Body Discomfort:

Taken after:	Area (Greatest Discomfort)	Intensity	Other areas of discomfort	Intensity
1st Hour				
2nd Hour				

Appendix C: Psychophysical Rating Scales

Rating of Perceived Exertion (RPE) Scale

Body Discomfort Map and Rating Scale (BDS)

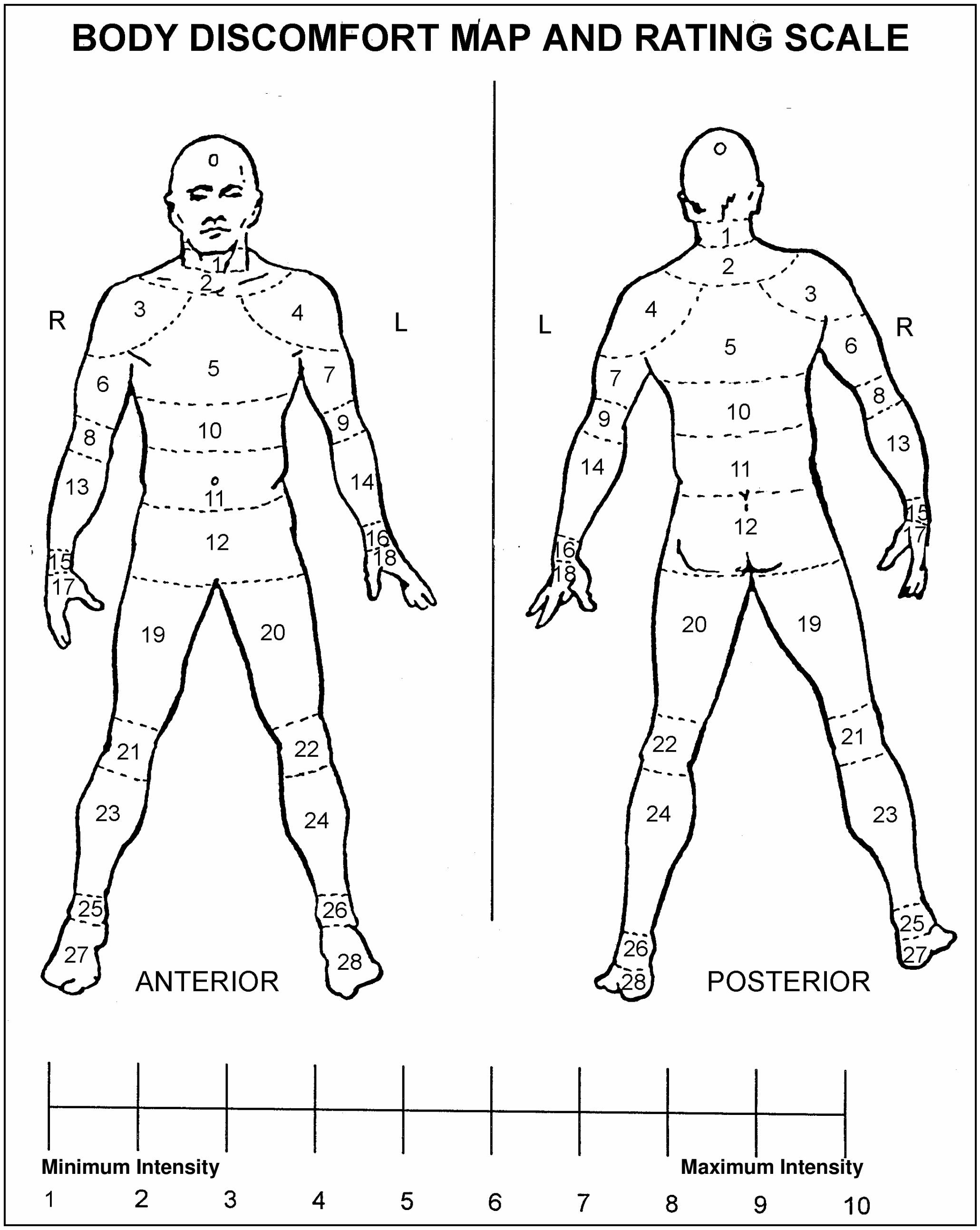
Body Contribution Map and Rating Scale

Rating of Perceived Exertion (RPE) Scale

Rating of Perceived Exertion	**(Borg, 1971)**
6	
7	**VERY, VERY LIGHT**
8	
9	**VERY LIGHT**
10	
11	**FAIRLY LIGHT**
12	
13	**SOMEWHAT HARD**
14	
15	**HARD**
16	
17	**VERY HARD**
18	
19	**VERY, VERY HARD**
20	

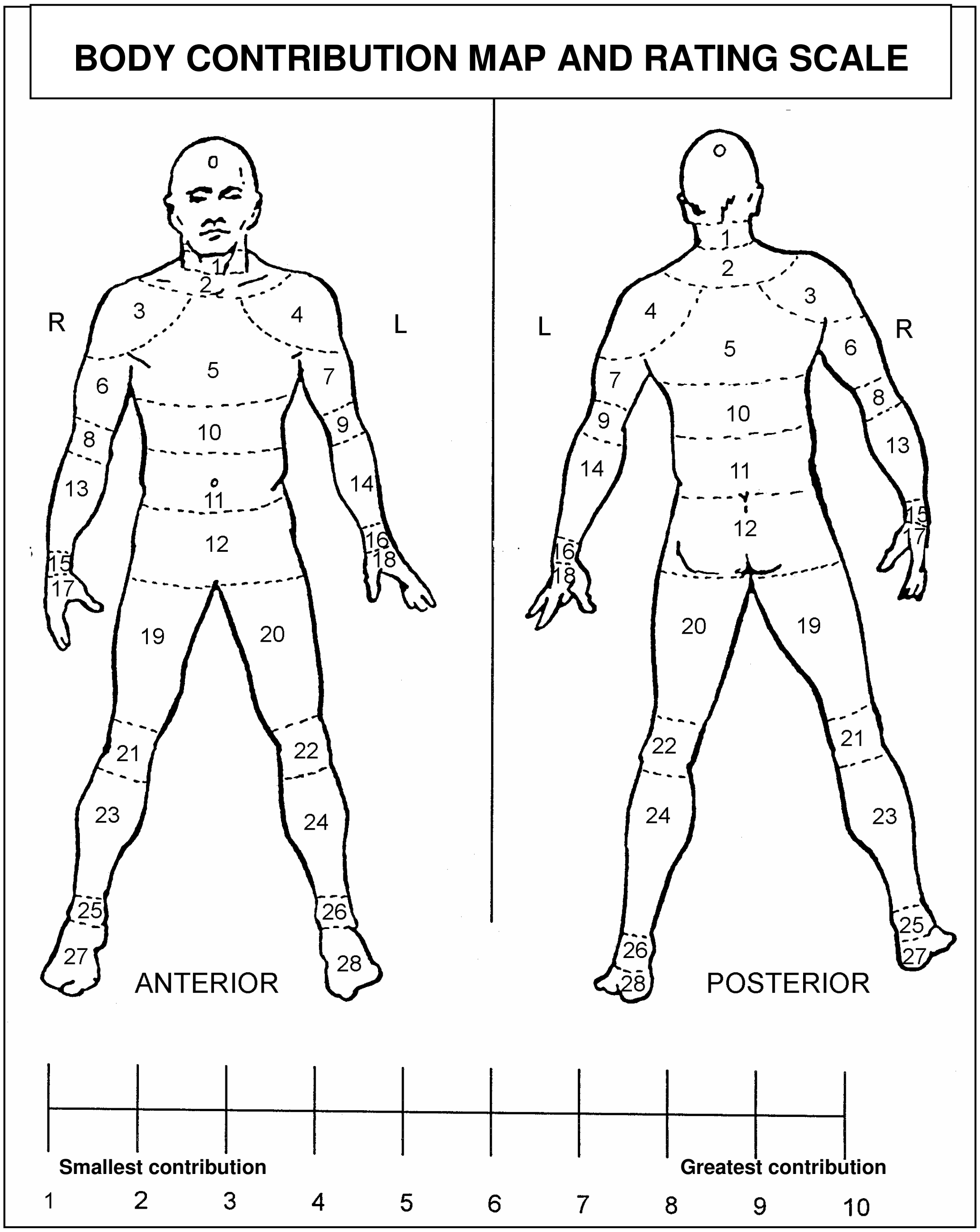
(Adapted from: Borg G (1971). **The Perception of Physical Work.** In: Shephard RJ (Ed.) Frontiers of Fitness, Springfield, Illinois: C Thomas).

Body Discomfort Map and Rating Scale (BDS)



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

Body Contribution Map and Rating Scale



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

(From: James J, Cripwell A and Furney S (2005). Pushing vs. Pulling Strength: Effect of Handle Height and Practical Ergonomics Applications. In: Thatcher A, James J and Todd A (Eds.). **CD-ROM Proceedings of CybErg'2005: The Fourth International Cyberspace Conference on Ergonomics 2005.** The International Ergonomics Association Press, University of the Witwatersrand, Johannesburg, South Africa).

Appendix D: Summary Reports

Heart Rate Printouts

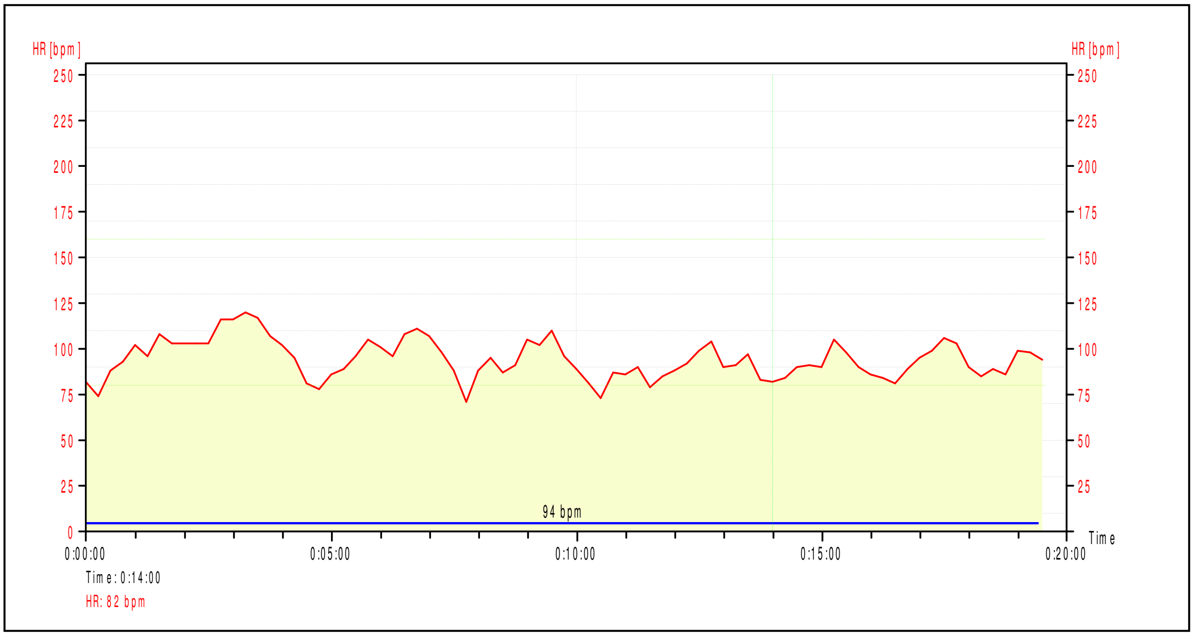
Accelerometer Printout

Printout from Enraf-Nonius EN-TreeM System

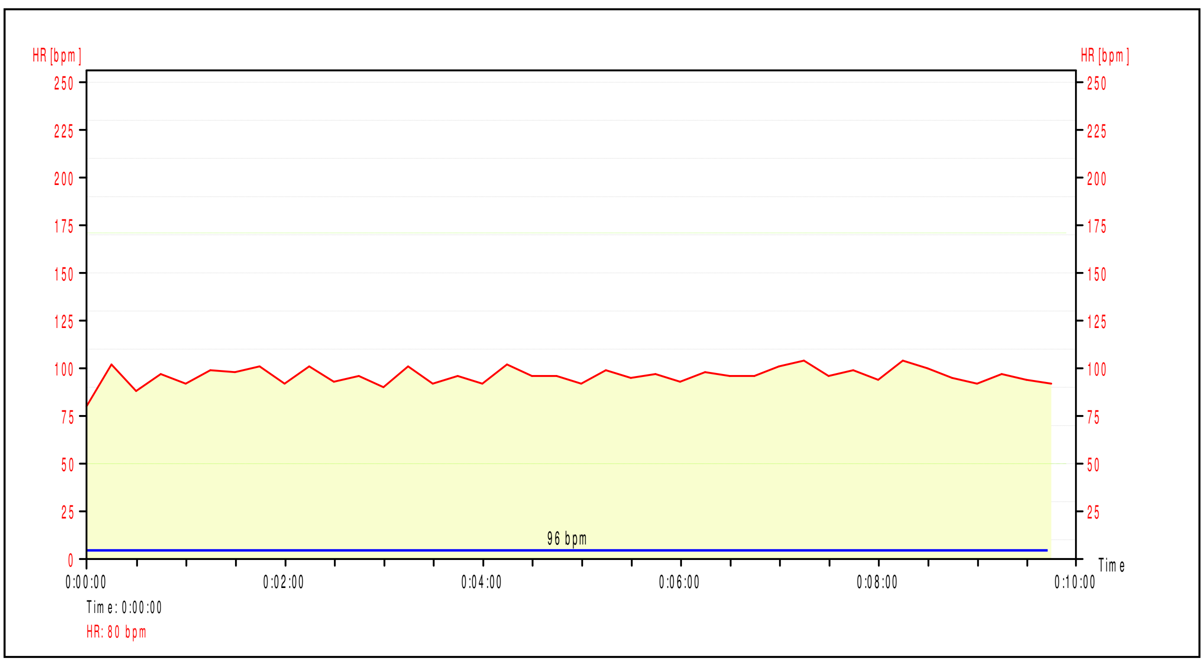
Example of Postural Analyses

Printout from Statistical Package

Heart Rate Printouts



Example heart rate printout from the PTT laboratory testing



Example heart rate printout from the CDC laboratory testing

Accelerometer Printout

User ID	007	
User Height	180	cm
User Weight	72.2	Kg
User Age	32	
User Gender	0	Male
User AMR	1.3242	Calories per Minute
Test Info:		
Notes		
Activity Data:		
Download Time	06/30/2004	21:17:58
Start Time	06/29/2004	23:25:00
Format	3	XYZ 1 Minute
Number Readings	1312	

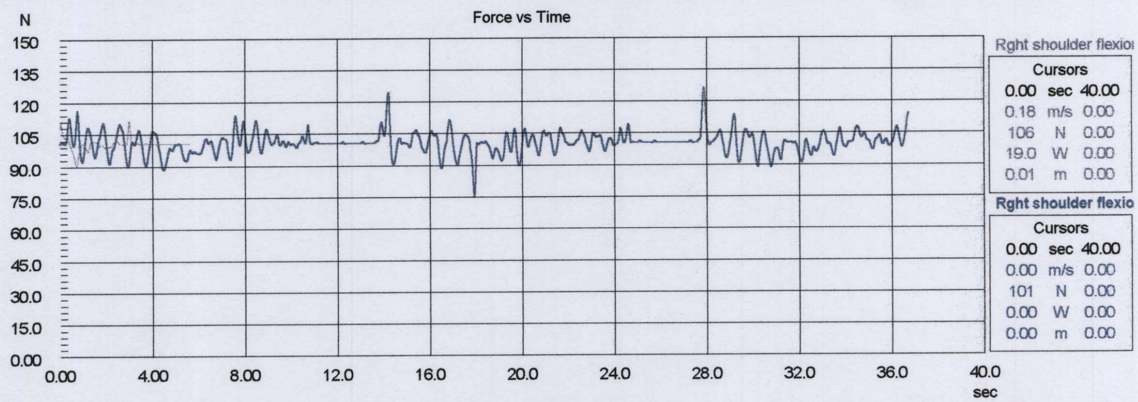
Entry	Date	Time	Total Calories	Activity Calories	VM	ActCntsX	ActCntsY	ActCntsZ
63	06/30/2004	00:27:00	2.6424	1.3182	490.33	391	270	121
64	06/30/2004	00:28:00	1.3888	0.0646	23.937	19	14	4
65	06/30/2004	00:29:00	2.0828	0.7586	281.61	192	159	131
66	06/30/2004	00:30:00	1.4614	0.1372	51	34	34	17
67	06/30/2004	00:31:00	2.2927	0.9685	359.79	193	224	205
68	06/30/2004	00:32:00	5.0422	3.718	1381.9	982	690	685
69	06/30/2004	00:33:00	1.335	0.0108	4.243	3	3	0
70	06/30/2004	00:34:00	3.8208	2.4966	927.57	625	509	459
71	06/30/2004	00:35:00	2.9303	1.6061	597.1	380	357	291
72	06/30/2004	00:36:00	2.2873	0.9631	357.82	199	244	170
73	06/30/2004	00:37:00	1.6901	0.3659	135.6	59	115	41
74	06/30/2004	00:38:00	1.9645	0.6403	238.44	168	135	102
75	06/30/2004	00:39:00	1.7116	0.3874	144.37	77	108	57
76	06/30/2004	00:40:00	1.5878	0.2636	98.346	34	80	46
77	06/30/2004	00:41:00	2.0129	0.6887	256.26	167	148	126
78	06/30/2004	00:42:00	2.1098	0.7856	291.8	165	189	149
79	06/30/2004	00:43:00	1.6578	0.3336	124.28	57	64	90
80	06/30/2004	00:44:00	1.7304	0.4062	151.4	114	81	58
81	06/30/2004	00:45:00	1.5367	0.2125	78.873	29	66	32
82	06/30/2004	00:46:00	1.8649	0.5407	200.72	85	124	133
83	06/30/2004	00:47:00	2.1716	0.8474	314.66	192	159	192
84	06/30/2004	00:48:00	1.456	0.1318	49.346	25	17	39
85	06/30/2004	00:49:00	1.4856	0.1614	60.042	41	30	32
86	06/30/2004	00:50:00	1.6094	0.2852	105.89	69	76	26
87	06/30/2004	00:51:00	2.1609	0.8367	310.92	152	202	181
88	06/30/2004	00:52:00	2.4514	1.1272	419.17	299	241	168
89	06/30/2004	00:53:00	2.6182	1.294	480.93	293	260	279
90	06/30/2004	00:54:00	4.1086	2.7844	1035.2	600	596	597
91	06/30/2004	00:55:00	1.8757	0.5515	205.36	145	89	115
92	06/30/2004	00:56:00	3.5114	2.1872	812.79	576	425	385

Printout from Enraf-Nonius EN-TreeM System

Enraf-Nonius **EN-TreeM Pulley** **EN-Alysis**

RUDAC

Patient 1				Patient 2			
[redacted]							
ID-No	: 1	Movement	: Rght shoulder flexion	ID-No	: 1	Movement	: Rght shoulder flexion
Birth	:	Mode	: Single wire	Birth	:	Mode	: Single wire
Sex	: Male	Mass	: 20.0 kg	Sex	: Male	Mass	: 20.0 kg
Length	: cm	Protocol	: PTT Pulling	Length	: cm	Protocol	: Pushing Proto 1
Weight	: kg	Set	: 1	Weight	: kg	Set	: 1
Date	: 25-02-2001	Therapist	:	Date	: 25-02-2001	Therapist	:
Time	: 19:24:23	Repetitions	: 3	Time	: 19:33:21	Repetitions	: 3
Target	: -	Dominant side	Right	Target	: 125 W	Dominant side	Right

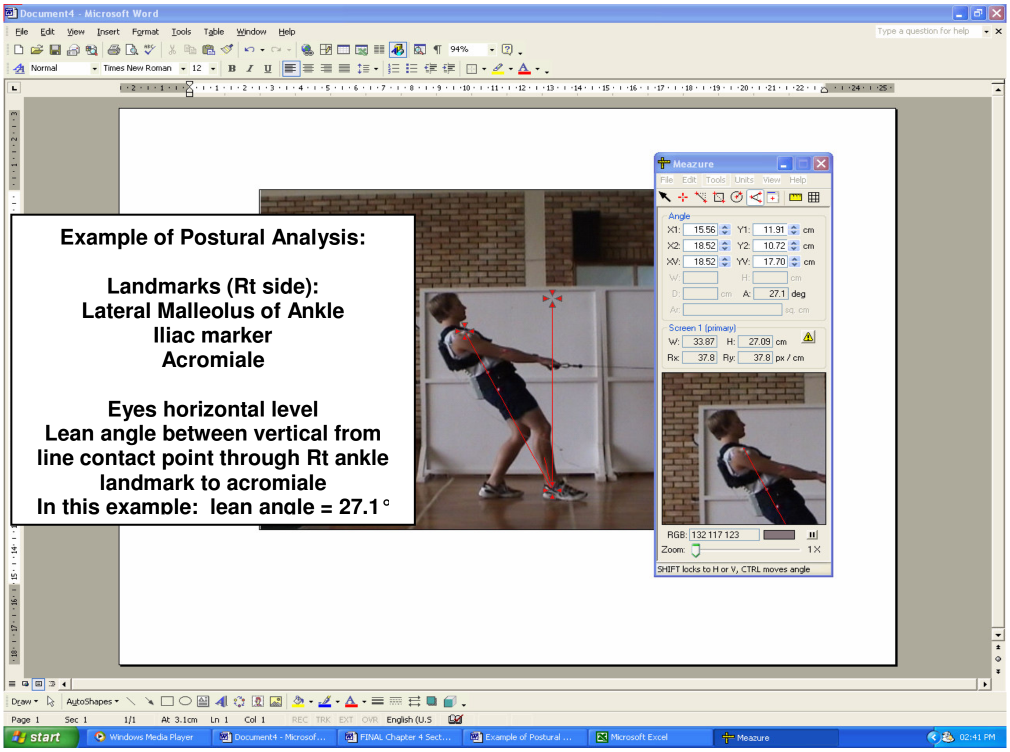


		Patient 1 /Rght shoulder flexion	Patient 2 /Rght shoulder flexion	Deficit
Repetitions	:	2	5	
Concentric				
Peak power	:	53.4 W	123 W	131.1 %
Avg peak power	:	26.8 W	60.3 W	124.9 %
Avg position at peak power	:	0.09 m	0.52 m	0.4 m
Avg power	:	17.9 W	18.4 W	2.7 %
Peak velocity	:	0.53 m/s	1.20 m/s	127.8 %
Avg peak velocity	:	0.26 m/s	0.58 m/s	120.8 %
Peak force	:	110 N	126 N	14.3 %
Avg peak force	:	106 N	95.5 N	-9.6 %
Total work	:	32.2 J	650 J	1919.0 %
Fatigue index	:	- Watt/rep	-9.71 Watt/rep	
Excentric				
Peak power	:	25.7 W	130 W	407.5 %
Avg peak power	:	9.03 W	57.5 W	536.7 %
Avg position at peak power	:	0.05 m	0.95 m	0.9 m
Avg power	:	5.16 W	22.4 W	333.3 %
Peak velocity	:	0.25 m/s	1.24 m/s	386.6 %
Avg peak velocity	:	0.09 m/s	0.55 m/s	520.2 %
Peak force	:	111 N	114 N	2.7 %
Avg peak force	:	104 N	106 N	1.9 %
Total work	:	33.4 J	839 J	2414.0 %

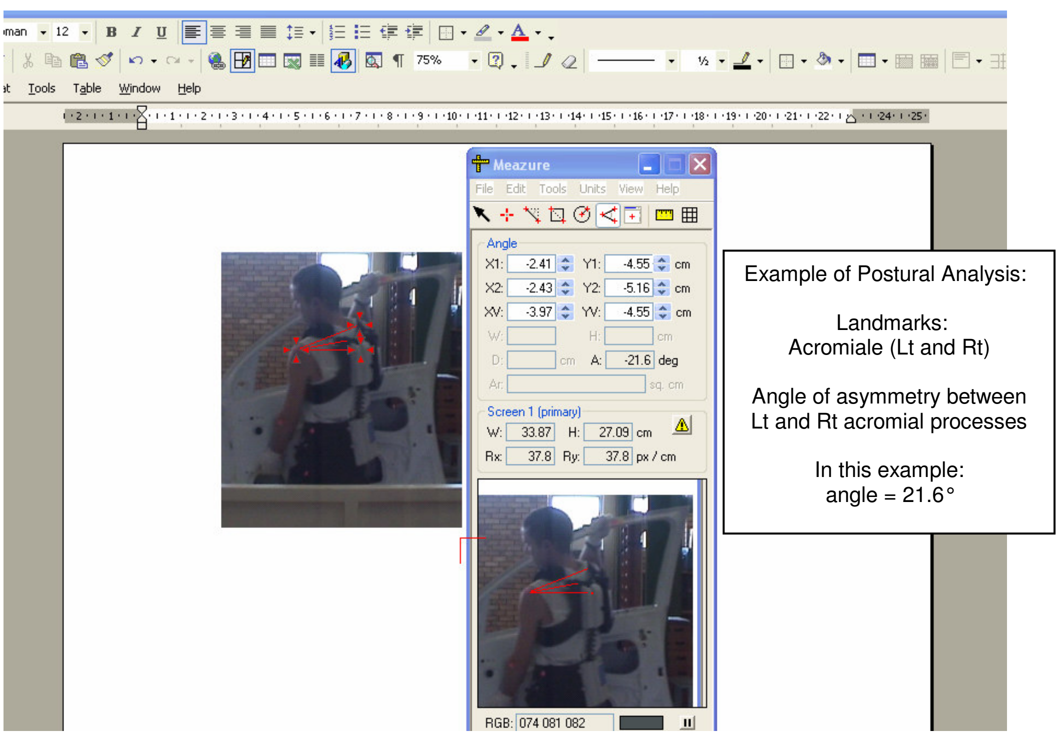
Rhodes University
Grahamstown
6140
SOUTH AFRICA
046-6223803

Example of Postural Analyses

Pulling postural analysis



Door carriage postural analysis



Printout from Statistical Package

Results from the STATISTICA (Version 7.0, StatSoft®) Programme

T-test for Dependent Samples (Spreadsheet1) Marked differences are significant at p < .05000								
	Mean	**Std.Dv.**	**N**	**Diff.**	**Std.Dv.**	**t**	**df**	**p**
1 Hand Pull	96.03333	14.25019						
2 Handed INT	90.40000	13.63970	30	5.633333	5.423342	5.689303	29	**0.000004**

T-test for Dependent Samples (Spreadsheet1) Marked differences are significant at p < .05000								
	Mean	**Std.Dv.**	**N**	**Diff.**	**Std.Dv.**	**t**	**df**	**p**
2 Handed Pull	90.40000	12.13601						
2 Handed INT	90.40000	13.63970	30	0.00	5.044628	0.00	29	1.000000

T-test for Dependent Samples (Spreadsheet1) Marked differences are significant at p < .05000								
	Mean	**Std.Dv.**	**N**	**Diff.**	**Std.Dv.**	**t**	**df**	**p**
1 Hand Pull	96.03333	14.25019						
2 Handed Pull	90.40000	12.13601	30	5.633333	6.332638	4.872383	29	**0.000036**

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(Directly and indirectly related to this research)

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