THE EFFECT OF RESTRICTED ENVIRONMENTS ON SELECTED POSTURAL, PHYSIOLOGICAL AND PERCEPTUAL RESPONSES

BY

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THESIS

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ABSTRACT

Manual lifting tasks are the predominant means of transporting materials in industry with many of these tasks being performed in confined spaces. Research has tended to focus on the biomechanical implications of working in small spaces with a decided lack of information about the physiological and perceptual responses in these environments. This holistic study therefore investigated the manner in which the human operator responded to conditions where the ceiling height was lowered and reach demands increased. Thirty-two young physically active male subjects (age: 21.55yr; stature: 1810mm) were recruited to complete a 2-way repeated measures experiment during which four lifting protocols where different combinations of ceiling height (‘normal’ or reduced to 1460mm in height) and reach demands (400mm or 800mm) were tested. A crude postural analysis was conducted while physiological responses were detailed and continuously monitored. Perceptual responses were also assessed.

The tasks with a ‘normal’ ceiling height (mean compression forces: 2615N; mean shearing forces: 388N) and the greatest reach distance (mean compression forces: 3655N; mean shearing forces: 386N) placed individuals under the highest strain. Mean heart rate (HR) responses were significantly lower ($p < 0.05$) in the URN condition when compared to the RF condition. Furthermore, HR responses were statistically significantly affected by the height of the ceiling and the reach depth. Statistically significant differences ($p < 0.05$) in mean tidal volume (V_T) occurred in the least (URN) and most (RF) restrictive conditions. Statistically significant differences ($p < 0.05$) in mean V_E were evident between URN and URF, between URN and RF and between RN and RF. Ceiling height and reach demands had a statistically significant effect on all respiratory responses. There was a statistically significant difference in mean oxygen consumption (VO_2) between the URN and all other conditions, and between the most restricted task (RF) and all other conditions. Both the effect of ceiling height and reach demands had a statistically statistically significant impact on VO_2. Respiratory quotient (RQ) was significantly higher when loads were moved over 800mm compared to 400mm yet ceiling height did not have a statistically significant effect on RQ. Mean energy expenditure was significantly higher in the RF condition compared to the two least restrictive conditions (URN and RN). Statistically significant differences in EE were also evident between URN and RN, and between URN and URF. EE was significantly affected by reductions in ceiling height and increases in reach demands.

Perceptually, the RF task (mean ‘Central’ RPE of 11) was perceived to place significantly greater cardiorespiratory demands on the operator compared to the URN (CRPE: 10) and RN (CRPE: 10) conditions. Statistically significant differences in perceived musculoskeletal strain only occurred between URN and RF. The effect of reach was perceived to have a statistically significant effect on both cardiovascular and musculoskeletal demands whereas ceiling height only had a statistically significant effect on musculoskeletal demands. The greatest discomfort was experienced in the lower back with the most intense discomfort occurring in the RN condition.

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INTRODUCTION

BACKGROUND TO THE STUDY

Manual materials handling (MMH) tasks are prevalent in industries around the world (Braam **et al**., 1996) resulting in workers frequently being exposed to highly hazardous physical workloads (Bales **et al**., 2001; Gilad and Boughanim, 2002; St-Vincent **et al**., 2005). With the majority of MMH tasks being performed in confined working environments (Drury **et al**. 1982; Drury, 1985; Ridd, 1985), the human operator is forced to adopt restricted working postures (Mital and Wang, 1989) often for extended periods of time which places strain on the musculoskeletal and cardiovascular systems. In Industrially Developing Countries (IDCs) these conditions are aggravated by the poor industrial infrastructure, a lack of adequate technology and inadequate and dangerous working conditions (Mohan, 1987). All these factors lead to a substantially greater demand being placed on the human operator as the majority of tasks are still being performed manually either by lifting, lowering, pushing, pulling or carrying materials (Dempsey, 1998).

Research conducted in First World Countries has demonstrated that lifting is the predominant MMH task, with many workers moving as much as 45 000kg per day (Bales **et al**., 2001). According to authors such as Abeysekera **et al**. (1990), Li (1992) and Olivier and Scott (1994), however, workloads within IDCs are considerably greater than those found in developed countries yet much of the research into MMH tasks executed in sub-optimal environments has been conducted and published in Industrially Advanced Countries

(Dempsey **et al**., 2000). This has in turn resulted in a severe lack of knowledge about some of the most taxing activities in the developing world, thereby highlighting the need and importance of conducting research within developing countries.

Although lifting is usually investigated in ‘ideal’ and unrestricted conditions, reports from the warehousing, shipping, forestry and mining industries have emphasised that lifting tasks are frequently executed in restricted conditions (Ljungberg **et al**., 1989; Gallagher, 1991; Haslegrave **et al**., 1997; Mital **et al**., 1997; Kumar, 1999; Gallagher, 2005; St-Vincent **et al**., 2005; Christie, 2006) forcing individuals to adopt awkward postures. These postures can include partial or fully stooped and squatting postures, lifting while kneeling or lying down, or a posture which is a combination of these, causing more strain on the worker (Mital **et al**., 1997; Gallagher **et al**., 2002). The variations in lifting postures result in decreases in performance (Drury, 1985) and further aggravate the musculoskeletal and cardiovascular stresses already experienced during lifting activities. Research conducted in the mining industry has demonstrated that when adopting restricted postures, workers estimate lower maximum acceptable weights of lift (Gallagher **et al**., 1988; Gallagher and Unger, 1990; Gallagher, 1991; Gallagher and Hamrick, 1992), experience substantial changes in strength capability (Kumar and Garand, 1992; Kumar, 1994), experience increases in intra-abdominal pressure (Sims and Graveling, 1988; Ayoub and Mital, 1989) together with noticeable alterations in muscle recruitment patterns (Floyd and Silver, 1955; Gallagher **et al**., 2002). There is also a greater physiological cost associated with awkward working postures in restricted environments (Gallagher and Unger, 1990; Gallagher **et al**., 1994; Gallagher, 2005), with Gallagher (2005) identifying that the physiological cost is a product of the specific task and the posture adopted. While lifting under constrained conditions the human operator is often forced to reach beyond the zone of convenient reach to obtain a load resulting in statistically significantly reduced isometric and isokinetic strength (Kumar and Garand, 1992), increased spinal loading (Ozkaya and Nordin, 1999) and shearing forces (Ferguson **et al**., 2002), higher erector spinae activity levels (McKean and Potvin, 2001) and an elevated physiological cost (Sengupta and Das, 2004).

Although research is available about lifting in unrestrictive environments, information regarding the biomechanical, physiological and psychophysical responses of the human operator lifting in restrictive environments is limited. Furthermore, to the author’s knowledge there is no information regarding an individual’s response in restricted environments where loads are lifted symmetrically and placed at increasing distances away from the origin of the load. This gap in the literature can be attributed to the difficulties associated with assessing tasks within restrictive environments highlighting the importance of developing methods for confined task assessment. This specific investigation therefore used basic assessment techniques such as digital images to crudely assess biomechanical strain and more detailed physiological measures (heart rate, breathing responses, oxygen consumption, respiratory quotient, energy expenditure) together with the Rating of Perceived Exertion scale to evaluate perceptions of effort and the Body Discomfort Scale to determine the degree of physical strain experienced. These responses were evaluated to determine the impact of the interaction between ceiling height restriction and horizontal reach distance on the human operator.

STATEMENT OF THE PROBLEM

Restrictions within the workplace are prevalent around the world, forcing the human operator to adopt awkward working postures. The strain on the individual is further aggravated when workers are required to reach and work outside of the zone of convenient reach while moving loads over obstacles found within the workspace. Although research has been conducted separately on restrictive working environments and working outside of the zone of convenient reach, there is a relative lack of information regarding the interaction of these two factors on the human operator. The focus of this study was therefore to investigate how the human operator adapted to industrial constraints working outside their zone of convenient reach. This was executed by taking a holistic approach.

RESEARCH HYPOTHESIS

The research hypothesis proposes that the interaction of a reduced ceiling height and increased reach demands will significantly increase physical responses. It is further hypothesised that the physiological and perceptual responses during lifting in restricted and unrestricted environments will differ significantly and that increases in horizontal reach distances will further affect these responses.

STATISTICAL HYPOTHESES

Hypothesis I:

The null hypothesis (H_o) proposed is that there will be no difference in the physiological responses between the four conditions:

a) H_O: $\mu_{\text{CV responses (URN)}} = \mu_{\text{CV responses (RN)}} = \mu_{\text{CV responses (URF)}} = \mu_{\text{CV responses (RF)}}$

H_a: $\mu_{\text{CV responses (URN)}} \neq \mu_{\text{CV responses (RN)}} \neq \mu_{\text{CV responses (URF)}} \neq \mu_{\text{CV responses (RF)}}$

b) H_o: $\mu_{\text{R responses (URN)}} = \mu_{\text{R responses (RN)}} = \mu_{\text{R responses (URF)}} = \mu_{\text{R responses (RF)}}$

H_a: $\mu_{\text{R responses (URN)}} \neq \mu_{\text{R responses (RN)}} \neq \mu_{\text{R responses (URF)}} \neq \mu_{\text{R responses (RF)}}$

c) H_O: $\mu_{\text{VO2 responses (URN)}} = \mu_{\text{VO2 responses (RN)}} = \mu_{\text{VO2 responses (URF)}} = \mu_{\text{VO2 responses (RF)}}$

H_a: $\mu_{\text{VO2 responses (URN)}} \neq \mu_{\text{VO2 responses (RN)}} \neq \mu_{\text{VO2 responses (URF)}} \neq \mu_{\text{VO2 responses (RF)}}$

d) H_O: $\mu_{\text{RQ responses (URN)}} = \mu_{\text{RQ responses (RN)}} = \mu_{\text{RQ responses (URF)}} = \mu_{\text{RQ responses (RF)}}$

H_a: $\mu_{\text{RQ responses (URN)}} \neq \mu_{\text{RQ responses (RN)}} \neq \mu_{\text{RQ responses (URF)}} \neq \mu_{\text{RQ responses (RF)}}$

e) H_O: $\mu_{\text{E responses (URN)}} = \mu_{\text{E responses (RN)}} = \mu_{\text{E responses (URF)}} = \mu_{\text{E responses (RF)}}$

H_a: $\mu_{\text{E responses (URN)}} \neq \mu_{\text{E responses (RN)}} \neq \mu_{\text{E responses (URF)}} \neq \mu_{\text{E responses (RF)}}$

Hypothesis II:

The null hypothesis (H_o) proposed is that there will be no difference in the perceptual responses between the four conditions:

a) H_O: $\mu_{\text{CRPE responses (URN)}} = \mu_{\text{CRPE responses (RN)}} = \mu_{\text{CRPE responses (URF)}} = \mu_{\text{CRPE responses(RF)}}$

H_a: $\mu_{\text{CRPE responses (URN)}} \neq \mu_{\text{CRPE responses (RN)}} \neq \mu_{\text{CRPE responses (URF)}} \neq \mu_{\text{CRPE responses (RF)}}$

b) H_O: $\mu_{\text{LRPE responses (URN)}} = \mu_{\text{LRPE responses (RN)}} = \mu_{\text{LRPE responses (URF)}} = \mu_{\text{LRPE responses (RF)}}$

H_a: $\mu_{\text{LRPE responses (URN)}} \neq \mu_{\text{LRPE responses (RN)}} \neq \mu_{\text{LRPE responses (URF)}} \neq \mu_{\text{LRPE responses (RF)}}$

Hypothesis III:

The null hypothesis (H_o) proposed is that there will be no difference in physiological and perceptual responses when a comparison is made between conditions where there is no ceiling restriction and when the height of the ceiling is reduced.

a) $H_O: \mu_{\text{PP responses (no ceiling restriction)}} = \mu_{\text{PP responses (with ceiling restriction)}}$

$H_a: \mu_{\text{PP responses (no ceiling restriction)}} \neq \mu_{\text{PP responses (with ceiling restriction)}}$

Hypothesis IV:

The null hypothesis (H_o) proposed is that there will be no difference in physiological and perceptual responses when a comparison is made between conditions where the depth of reach was 400mm and when the reach distance was 800mm.

a) $H_O: \mu_{\text{PP responses (400mm reach)}} = \mu_{\text{PP responses (800mm reach)}}$

$H_a: \mu_{\text{PP responses (400mm reach)}} \neq \mu_{\text{PP responses (800mm reach)}}$

Where:
R = restricted working environment
UR = unrestricted working environment
N = moving the load over 400mm
F = moving the load over 800mm
CV = cardiovascular
R = respiratory
VO_2 = oxygen uptake
RQ = respiratory quotient
E = energy expenditure
CRPE = 'Central' Rating of Perceived Exertion
LRPE = 'Local' Rating of Perceived Exertion
PP = physiological and perceptual

DELIMITATIONS

Thirty-two physically active young male students ranging in stature from 1750mm to 1900mm volunteered as subjects. Subjects were required to attend one habituation, and two testing sessions. After consenting to participate in the investigation, anthropometric and strength data (stature, mass and grip strength) were recorded during the habituation session.

Subjects then returned to the laboratory to perform two lifting protocols (ceiling height restricted to 1460mm or an unrestricted ceiling height) for a duration of six minutes per lifting task at a lifting frequency of 6lifts.min^{-1}. The lifting protocol required subjects to lift and place a 12kg load either 400mm or 800mm away from its origin. An assistant returned the load to its initial starting position. The posture adopted while performing the lifting activity was recorded digitally, while physiological responses (heart rate, breathing responses, oxygen consumption, respiratory quotient and energy expenditure) were measured directly during the testing period using a heart rate monitor (Polar® S410) and an online metabolic ergospirometer (Cosmed K4b$^{2®}$). The subject's perception of how taxing the lifting tasks were on the cardiorespiratory and musculoskeletal systems was assessed through the use of Borg's Rating of Perceived Exertion (RPE) scale every three minutes during the lifting protocols. On completion of each of the lifting protocols, subjects were required to provide information on areas of the body experiencing discomfort and the intensity of the discomfort through the use of the Body Discomfort Map.

LIMITATIONS

Male subjects were used during this investigation, as this is the predominant industrial population. The data reported in this study may therefore not be applicable to females.

The subjects recruited for this study were drawn from a student population with many of the subjects lacking training or experience in industrial lifting tasks, which could in turn affect the reliability and validity of their responses. Individuals accustomed to industrial tasks are hypothesised to have reduced spinal loading (Ferguson **et al**., 2002). Furthermore, these individuals may have perceived the task in a manner that could negatively affect the individual's responses (Snook **et al**., 1978; Mital, 1987). In order to minimise the effect of the subject's inexperience, subjects were provided with instructions and 'training' on the manner in which the lifting tasks should be performed prior to the test sessions. Furthermore, as the subjects lacked experience working within restricted environments, Legg (1986) reports that these individuals may have higher energy expenditures than those accustomed to working within confined spaces. The responses recorded during this investigation may therefore not be an accurate representation of actual responses recorded in workers adapted to performing within confined environments. However, as the main focus of this investigation was to compare how the human operator responded under the four different conditions, the differences between these responses was the key factor.

This investigation was conducted within a laboratory to ensure that external factors that may affect the sample's responses were tightly controlled. The results of this study may therefore not be comparable to responses recorded *in situ*.

Although these factors are known to affect the responses of individuals, all aspects of the study were rigorously regulated to reduce the effect of external factors on the subjects responses.

CHAPTER II

REVIEW OF RELATED LITERATURE

INTRODUCTION

Within industries around the world manual materials handling (MMH) tasks are the predominant means of moving materials whether through lifting, lowering, pushing, pulling or carrying (Snook **et al**., 1978; Sanders and McCormick, 1992; Capodaglio **et al**., 1997; Mital **et al**., 1997). Furthermore, although the importance of a good working posture was recognised as early as the eighteenth century by Ramazzini (1713), many manual labourers are forced to adopt uncomfortable and restricted postures due to the layout of the workspace (Mital and Wang, 1989). This is specifically the case in Industrially Developing Countries (IDCs) where workstations do not have a high degree of adjustability. Lifting, as the most prevalent MMH task (Ciriello, 2003), has been researched extensively due to the prevalence of lower back pain reports (Kumar, 1994; Marras **et al**., 1999) yet in-depth holistic investigations into the implications of lifting while working in industries that have restrictions, such as mining, construction, forestry, packing, warehousing and shipping (Gallagher and Unger, 1990; Gallagher and Hamrick, 1992; Rückert **et al**., 1992; Gallagher **et al**., 1994; Pal and Sinha, 1994; Gallagher, 2005; Korkmaz **et al**., 2006; Splittstoesser **et al**., 2007) are limited. Moreover, literature reporting on the impact of working within occupational environments where the ceiling is lowered and the human operator is forced to reach to place loads is even less frequently encountered hence this was the focus of the current investigation.

RESTRICTIVE WORKING ENVIRONMENTS

Restrictive working spaces are prevalent worldwide (Drury, 1985) with workers frequently being restricted either vertically or laterally (Gallagher, 2005). Obstacles located within the workspace and excessive reach demands are also common further restricting the human operator (Haslegrave **et al**., 1997). Certain occupations require the periodic adoption of awkward postures such as nursing, cleaning, sheep shearing, hand cultivation and harvesting of fruit and vegetables together with maintenance and repair work (van Wendel de Joode **et al**., 1997; Lemasters **et al**., 1998; Nussbaum and Torres, 2001; Menzel **et al**., 2004; Earle-Richardson **et al**., 2006; Faucett **et al**., 2007; Kumar and Kumar, 2007; Milosavljevic **et al**., 2007; van der Molen **et al**., 2007). These occupations necessitate stretching forward to obtain and lift a load, and reaching over and/or around equipment (Haslegrave, 1994; Reynolds **et al**., 1994; Haslegrave **et al**., 1997). Other industrial environments considered to be severely restricted include aircraft holds (Rückert **et al**., 1992), mine seams (McPhee, 2004; Torma-Krajewski **et al**., 2007) and warehousing and packing industries (Braam **et al**, 1996; Kumar, 1999; St-Vincent **et al**., 2005) where in fact, more prolonged adoption of ‘unnatural’ postures are observed. For example, aircraft baggage handlers are expected to stow luggage in areas with vertical dimensions ranging between 0.8m and 1.76m depending on the aircraft (Rückert **et al**., 1992; Korkmaz **et al**., 2006). Miners often work in areas with vertical restrictions ranging between 0.5m and 1.2m (Gallagher and Unger, 1990; Gallagher, 1991; Gallagher and Hamrick, 1992; Gallagher **et al**., 1994) and warehousing workers also experience vertical constraints (Ljungberg **et al**., 1989; Kuorinka **et al**., 1994; St -Vincent **et al**., 2005). Furthermore, these workers are often expected to place loads outside their zone of convenient reach.

Although a range of tasks can occur in constrained environments, lifting tends to be prevalent (Kumar, 1999). The performance of lifting tasks requires that the human operator adopts varying postures depending on task constraints. Examples of these postures include stooping, squatting, kneeling or lying down in order to lift loads. The lifting posture assumed is therefore determined by the task demands placed on the individual’s visual, reach, manipulative, strength and endurance capacities yet the posture is restricted by the interaction of the anthropometric dimensions of the human operator and the layout of the workspace (Haslegrave, 1994). A working posture thus varies considerably and is dependent on the task, the workstation, the particular design of the working tool and the operator’s unique anthropometry (Haslegrave, 1994; Pheasant, 2001; Vieira and Kumar, 2004). Unrestricted environments permit the human operator to alternate between various lifting postures, easing the load on the musculoskeletal system. In contrast, in restrictive environments, individuals are often forced into selecting a single posture without the opportunity to reduce the discomfort experienced (Drury, 1985; Gallagher, 2005). This is due to either a partial restriction, where only a certain region of the body is required to be moved around an obstacle, or a complete restriction where the individual may be completely restricted and the body is confined to a predetermined zone (Mozrall **et al**., 2000). Constraints therefore compel the human operator to choose awkward postures when moving loads in order to accommodate the individual’s unique anthropometry and avoid discomfort (Kuorinka **et al**., 1994). It is therefore apparent that as conditions change, the posture adopted will also change. Aggravating these occupational demands further, is that many of the mechanical devices available to reduce task demands in unrestricted environments are unsuitable for use in confined spaces due to their dimensions (Gallagher, 2005).

Due to the fact that cramped working environments limit the postures adopted and the ability to reduce the stress experienced by the worker through the use of mechanical aids, the human operator endures additional biomechanical, physiological and perceptual strain. In general, individuals adopting unfavourable postures report feeling postural stress, fatigue and pain (Corlett, 1981; Haslegrave, 1994; Maiti and Ray, 2004; Vieira and Kumar, 2004; Gallagher, 2005). Feelings of fatigue are however one of the most prevalent complaints in tasks where the body is arranged in an ungainly position (Haslegrave **et al**., 1997). The degree to which an individual is stressed is nevertheless dependent on factors such as the posture adopted, the task demands and the worker’s capabilities and can manifest itself in either one or a combination of musculoskeletal, physiological or perceptual responses.

LIFTING IN AWKWARD ENVIRONMENTS

The main focus of this study was to assess the combined effect of a reduction in ceiling height and varying reach demands and as such, the musculoskeletal, physiological and perceptual effects of lifting in varying awkward environments is highlighted. This holistic approach was adopted in the current study.

MUSCULOSKELETAL EFFECTS

Due to the demands of general lifting tasks, workers tend to adopt either a stoop or squat lifting posture although a combination of these two postures is also seen. Squat postures tend to be recommended by medical practitioners as this posture is considered to reduce the impact on the spinal column while working the stronger leg muscles (Ayoub and Mital, 1989; van Dieën **et al**., 1999; Lindbeck and Kjellberg, 2001; Straker, 2003; Bazrgari **et al**., 2007). Furthermore, this posture enables individuals to work at a mechanical advantage due to a longer moment arm (Bridger, 2003), yet a lower maximal acceptable weight of lift is lifted in this posture (Straker and Duncan, 2000). Moreover, with vertical restrictions in place a squatting posture can be preferential, as the individual does not place extra strain on the lower back. This posture is also associated with lower peak compression forces (Ayoub and Mital, 1989), less strain on the lower back ligaments (Anderson and Chaffin, 1986), and a greater degree of postural stability (Puniello **et al**., 2001).

Most individuals, however, tend to naturally adopt a stooped posture during lifting tasks (Straker, 2003; Trafimow **et al**., 1993) especially when heavy loads need to be lifted, extreme force needs to be exerted or when extra mobility is required (Gallagher and Hamrick, 1992; Gallagher **et al**., 2002). A stooped lifting posture is nevertheless associated with more pronounced shearing forces and 75% greater bending torques (Ayoub and Mital, 1989; Dolan **et al**., 1994; Gallagher **et al**., 1994; Hsiang **et al**., 1997; Gallagher **et al**., 2002; Gallagher, 2005), which contribute to rapid fatiguing of the spinal tissues (Gallagher, 2003). In contrast, compression and peak extensor moments are substantially lower as the operator is not required to lift both their body weight and the load (Patridge and Duthie, 1968; Leskinen **et al**., 1983; Ayoub and Mital, 1989; Dolan **et al**., 1994; Gallagher **et al**., 1994; Hsiang **et al**., 1997; Straker, 2003; Gallagher, 2005). It is however recommended that stooped postures are not adopted in cramped environments due to the reduced compressive tolerance of the spine (Adams and Hutton, 1982) and the high degree of shearing forces experienced (Gallagher **et al**., 2002).

In addition to these postures, individuals can also kneel or lie down in order to move loads. It is interesting to note that of all these, kneeling postures tend to be chosen most frequently (McMillan and Nichols, 2005). Lifting while kneeling is associated with the lowest level of shearing forces (Waters **et al**., 1993; Gallagher **et al**., 2002), but 22 – 24% higher peak compression forces (Gallagher **et al**., 1994) than stooped lifting. Static lifting forces produced while kneeling are 44% greater than lifting forces produced while standing (Haslegrave **et al**., 1997), even though trunk extension strength is 16% less when kneeling (Gallagher, 1997). Gallagher (1997) identified that even though trunk extension is less than when kneeling, activity levels of the trunk muscles remained the same. This author therefore concluded that this reduction in trunk extension strength could be attributed to a decrease in the ability of the operator to strongly rotate their pelvis. Furthermore, lifting capacity in kneeling postures is 11 – 15% lower than stooping (Gallagher and Unger, 1990; Gallagher, 1991) due to the force production for the lifting action originating predominantly from the arm and trunk muscles as limited assistance is available from the lower extremity. Furthermore, the stability of the base of support during kneeling is reduced (Gallagher and Unger, 1990; Gallagher, 1991). Gallagher and Hamrick (1992) argue however that the effect of posture may only be effective once a predetermined weight limit has been reached.

Kneeling postures have also been linked to the development of knee pain (O'Reilly **et al**., 2000), knee osteoarthrosis (Jensen and Eenberg, 1996; Sandmark **et al**., 2000) and knee osteoarthritis (Coggon **et al**., 2000; Manninen **et al**., 2002). Moreover, adopting a kneeling posture places the individual at a distinct movement disadvantage as the human operator is not able to move with the same agility (Splittstoesser **et al**., 2007). Even though each of the lifting techniques has their own distinct advantages and disadvantages, research has shown that all these postures are associated with the development of musculoskeletal disorders (Waters **et al**., 1998).

On examining the specific impact of lifting within restricted areas, Rückert **et al**. (1992) and Elfeituri (2001) explain that reductions in headroom cause subjects to fully flex their trunks thereby increasing the mechanical disadvantage which in turn is associated with increases in spinal compression. More recent findings regarding spinal loading revealed that as the vertical height available to move in is reduced, so lumbar moments increased regardless of the posture adopted (Gallagher **et al**., 2001). Splittstoesser and associates (2007) however contend that increasing the height of the ceiling would potentially result in a reduction in spinal loading as workers would be able to use a more upright posture. However, these authors argue that the highest degree of spinal loading occurs during the initiation of the lift, which would therefore not be affected by the extent of the ceiling height. Due to the nature of the constrained workplace, many workers spend long durations in forward flexed postures causing the erector spinae muscle to fatigue. Lumbar flexion is therefore seen to increase and in turn affects the individual's proprioceptors and ability to perceive the position of their body (Tamela **et al**., 1999) leading to a significantly higher risk of developing lower back pain (Neumann **et al**., 2001). Although posture is important in restricted conditions, other factors also affect the human operator's responses. The mass of the load lifted while working in constrained conditions is directly related to the degree of compression and shearing forces (Splittstoesser **et al**., 2007), which according to the NIOSH (1981) lifting guideline should not be greater than 3400N in the case of compression forces and shearing forces should be less than 1000N (McGill, 1996). The loading of the spinal column can however be reduced by ensuring that the load has adequate handles (Marras **et al**., 1999), as poorly designed loads can limit lifting capacity to such an extent that the effects of posture are no longer evident (Gallagher and Hamrick, 1992). A further disadvantage associated with a reduction in roof height is that subjects experience an alteration in the manner in which the usual symmetrical lifting action is used (Gallagher, 1991). Subjects are therefore not able to lift the load to as great a vertical height due to the ceiling restriction and therefore have to manoeuvre the load within the spatial restrictions.

According to Waters **et al**. (1993), Marras **et al**. (1999) and Plamondon **et al**. (2006), the location of the load on retrieval is reported to have the greatest influence on spinal loading. Research (Schipplein **et al**., 1995) suggests that as the initial placement of the load from the ankles increased from 400mm to 600mm, moments about L_5/S_1 doubled when compared to an increase from 200mm to 300mm. Compression forces in L_5/S_1 also increase as the origin of the load is moved further away (Ekblom **et al**., 1982). This is due to the spinal column being exposed to additional loading as a greater proportion of the weight of the body together with the load lifted is being held in position away from the spinal column (Waters **et al**., 1993; Ozkaya and Nordin, 1999; Ferguson **et al**., 2002; Plamondon **et al**., 2006). The maximum acceptable weight (MAW) lifted is also affected when reach demands are extreme and can decrease by between 33% and 46% (Ciriello, 2003; Ciriello, 2007). Gallagher and associates (2002) reported that adopting a kneeling posture when one knee is raised created a barrier to obtain the load and resulted in 43% greater spinal moments than a lift performed on two knees. It is therefore evident that occupational constraints can also be caused by the operator. The distance that a load is placed from the origin of the lift also plays a role in determining the strain experienced during task completion. Statistically significant increases in the peak compression forces in L_5/S_1 occur when the human operator lifts a load over a barrier largely because the individual moves the load further away from L_5/S_1 (McKean and Potvin, 2001; Budihardjo and Derrick, 2004). Moreover, the height of the barrier has also been demonstrated to have an effect on the spinal column with barrier heights of approximately knee height associated with greater stress on the lower back compared to barriers of lower and greater heights (Budihardjo and Derrick, 2004). Lifting the load from behind a barrier and placing it close to the operator also results in changes in spinal loading. Kingma and van Dieën (2004) demonstrated that lifting a load with two hands from behind a barrier resulted in significantly higher compression and shearing forces than when lifting with one hand.

The posterior deltoids (Habes **et al**., 1985) and lower back muscles are also exposed to greater stress when lifting and lowering at the extremes of the operator's reach capacity. As the relatively weak posterior deltoids are employed in arm extension (Habes **et al**., 1985; Tortora and Grabowski, 2000), overuse of these muscles can develop into a musculoskeletal disorder (Singholm **et al**., 1984). The latter authors identified that elevation of the upper arm when performing tasks that require reaching actions was the most important factor for the development of occupational cervicobrachial disorders. The additional strain that excessive reach demands place on the operator are further intensified when a restricted stoop lift is performed to a vertical height of 0.7m, as stoop lifting already relies heavily on the strength of the shoulders and upper extremities (Gallagher and Hamrick, 1992). Although no research, to the author's knowledge, has been conducted on the interaction between reduced ceiling heights and excessive reach demands, it was hypothesised that the combination of these two factors would place the individual under a great deal of biomechanical and physiological strain thereby hastening the onset of fatigue.

PHYSIOLOGICAL EFFECTS

The effect of the load lifted and the frequency at which it is lifted have both been shown to significantly alter the human operator's physiological responses in unrestricted conditions (Drury **et al**., 1989; MacKinnon, 1999). Lifting frequency exerts the greatest influence with increases in lifting frequency being associated with greater elevations in heart rate (HR), oxygen consumption (VO_2) and energy expenditure than increases in load (Mital, 1980; Legg and Pateman, 1985; Ayoub and Mital, 1989; Welbergen **et al.**, 1991; MacKinnon, 1999). Body posture, although investigated to a lesser degree, has also been linked to changes in energy expenditure. Squat lifting postures for example, although considered to be beneficial from a biomechanical perspective, are physiologically more demanding (Kumar, 1984; Welbergen **et al.**, 1991; Sanders and McCormick, 1992; Straker, 2003) as is evident in Table I. Over an 8h working day, these differences can accumulate to as much as 20 – 30% or 3683.7kJ more than a stoop lifting posture (Garg and Herrin, 1979; Kumar, 1984), identifying a possible reason why individuals tend to switch from a squat to a stoop lifting posture over time (Trafimow **et al.**, 1993).

TABLE I: Physiological cost of squat and stoop lifts in unrestricted environments.

(Adapted from Kumar, 1984; Welbergen ***et al****., 1991).*

	Squat lift		**Stoop lift**	
	HR (bt.min^{-1})	**VO_2 (L.min^{-1})**	**HR (bt.min^{-1})**	**VO_2 (L.min^{-1})**
Kumar (1984)	▨	1.06	▨	0.68*
Welbergen **et al**. (1991)	134	1.90	116	1.42*

*Where: HR refers to heart rate; VO_2 refers to oxygen consumption; * refers to a statistically significant difference within the study.*

Squat and stoop lifting techniques are also utilised in restrictive environments although stoop lifting is preferred. Another preferred, or forced, posture is kneeling with comparisons between these two postures available but conflicting (refer to Table II). Gallagher and Unger (1990) showed that physiological responses (HR and VO_2) while kneeling are significantly higher than those measured during stooped lifting even though significantly less weight was lifted during kneeling (Table II). Another investigation by Gallagher (1991) however identifies that stoop lifting results in significantly higher VO_2 responses than kneeling lifts. The discrepancies between these two studies are due to Gallagher and Unger's (1990) subjects performing a lateral lifting action, which is associated with a greater energy expenditure whereas, in the latter study (Gallagher, 1991) subjects moved the load in the sagittal plane but over greater vertical distances leading to higher energy expenditure in the stooped posture. Gallagher and Hamrick (1992) reported similar findings with higher physiological responses in symmetrical stoop lifting when compared to symmetrical kneeling lifting however, Gallagher **et al**. (1988) found significantly higher HR and VO_2 responses in kneeling conditions compared to stoop lifting when the ceiling height was reduced to 1.2m. In general, however, the parameters of the lifting task are ultimately the deciding factor in determining which lifting posture is more physically demanding, with workers tending to curtail the energy cost of working by adapting to environmental demands rather than sparing the musculoskeletal system (Drury **et al**., 1989).

TABLE II: Physiological cost of stoop and kneeling lifts in restrictive environments.

(Adapted from Gallagher and Unger, 1990; Gallagher, 1991).

	Stooped lift		**Kneeling lift**	
	Mean HR ($bt.min^{-1}$)	**Mean VO_2 ($ml.kg^{-1}.min^{-1}$)**	**Mean HR ($bt.min^{-1}$)**	**Mean VO_2 ($ml.kg^{-1}.min^{-1}$)**
Gallagher and Unger (1990)	124	13.8	135*	15.6*
Gallagher (1991)	107	12.2	106	10.7*

*Where: HR refers to heart rate; VO_2 refers to oxygen consumption; * refers to a statistically significant difference within the study.*

Despite the effect of lifting posture on the rate of energy expenditure, the availability of headroom for workers has also been identified as a factor affecting physiological responses. Investigations in the mines, have established that there is an increased energy cost associated with working in restricted environments (Moss, 1934; Bedford and Warner, 1955). This is a finding supported by many (Sanders and McCormick, 1992; Gallagher, 2005; Han **et al**., 2005). More specifically, the greater the deviation from an upright standing position, the greater the energy cost to the human operator (Morrissey **et al**., 1985; Kumar **et al**., 1993; Kumar **et al**., 2000). This trend is also evident in the intra-abdominal pressure experienced, with reductions in headroom being linked to increases in pressure (Sims and Graveling, 1988). Furthermore, statistically significant increases in EMG activity within the erector spinae are evident at the start of the lift when reductions in headroom are present (Kumar, 1999). Legg (1986) has however reported that individuals exposed to environmental restrictions on a regular basis do not utilise energy to the same extent as those newly introduced to confined occupational tasks. This can be attributed to the adaptation of the body that occurs during regular task performance, resulting in development of muscle tissue and more efficient fuel utilisation which in turn delays the onset of fatigue.

Reach demands in partially restrictive environments have also been associated with an elevated physiological cost (Habes **et al**., 1985; Sengupta and Das, 2004). Although not reporting specifically on sagittal lifts, Sengupta and Das (2004) explain that retrieving and lifting loads from increasing reach distances can elevate significantly HR and VO_2 responses by as much as 14% and 52% respectively (Table III). Other research (Garg and Saxena, 1982; Habes **et al**., 1985) conducted on sagittal lifts where the distance across which the load is transported and placed increased, also reported that although differences in HR responses were evident, these were not statistically significant. Increases in reach distance placement, and hence HR are however associated with hastening the onset of fatigue and pain while contributing to reduced productivity.

TABLE III: Comparison between reach distances.

(Adapated from Sengupta and Das, 2004).

	HR ($bt.min^{-1}$)	% Increase^{+}	VO_2 ($L.min^{-1}$)	% Increase^{+}
'Normal' reach	95	0	0.52	0
'Maximum' reach	101*	6	0.62*	18
'Extreme' reach	108*	14	0.79*	52

*Where: HR refers to heart rate; VO_2 refers to oxygen consumption; * refers to a statistically significant difference between the 'normal', 'maximum' and 'extreme' reach conditions; $^{+}$ refers to the percentage increase in the responses from the 'normal' reach category.*

Increasing reach distances have also been shown to be associated with elevated muscular activity (Habes **et al**., 1985). Sengupta and Das (2004) identify more specifically that the activity of the anterior deltoids increased by 193%, the upper trapezius activity increased by 95% and the erector spinae activity increased by 106% when comparing the muscular load between load retrieval in the 'normal' and 'extreme' reach zones. Increasing the distance from the origin to where the load is placed from 'half' to 'full' reach is also associated with increases in muscle activity in both the deltoid and upper trapezius (Habes **et al**., 1985).

PERCEPTUAL EFFECTS

An individual's perception of the task plays a crucial role in their performance. In 'normal' work settings, increasing the load lifted and lifting frequency are known to place additional strain on the human operator and in doing so, elevates their perception of the difficulty of the task (Mital, 1980; Legg and Pateman, 1985; Welbergen **et al**., 1991; Olivier and Scott, 1994; Mital **et al**., 1997; MacKinnon, 1999; Wolfe, 2004). The lifting posture assumed has also been demonstrated to affect an individual's perception of the task. Subjects report that stoop lifting is subjectively less taxing on the entire body (Kumar, 1984; Wiker and Schultz, 1992; Straker and Duncan, 2000; Straker, 2003), whereas squat lifting postures are regarded as the most tiring perceptually (Kumar, 1984). Hagen and Harms-Ringdahl (1994) also hypothesise that stoop lifting will be perceptually less tiring on the quadriceps muscles thereby delaying the onset of whole-body fatigue. Furthermore, subjects prefer squat and kneeling lifting postures over stoop lifting despite the fact that lifting capacity in a stooped posture is only slightly less than the lifting capacity in an unrestricted standing posture (Gallagher and Hamrick, 1992). Gallagher and Hamrick (1992) hypothesise that this is linked to the degree of lumbar discomfort experienced.

With respect to postural constraints and lowered ceiling heights, there are increased levels of perceived discomfort (Corlett and Bishop, 1976). More specifically, lowered ceiling heights (height of 1.0m) are subjectively more taxing than performing tasks under a ceiling restriction of 1.4m (Rückert **et al**., 1992). Kumar and Lechelt (1999) and Kumar **et al**. (2000) contend however that neither Ratings of Perceived Exertion nor discomfort levels in the lower back and torso were significantly higher when comparing varying degrees of spatial restriction. Contradicting research by other authors (Kumar **et al**., 1993) reported that headroom availability was associated with a statistically significant increase in Rating of Perceived Exertion (RPE) thereby highlighting the individual nature of perceptual responses. Kumar **et al**. (1993) however suggests that higher perceptual responses in regions with lowered ceilings are linked to an increase in the perception of the heaviness of the load.

Increasing horizontal reach demands are associated with a statistically significant increase in the perception of task difficulty (Habes **et al**., 1985) with subjects who are required to work outside of their zone of convenient reach experiencing increased discomfort due to the muscles having to lift, hold and extend the load. Furthermore, lifting at the extremes of the human operator's reach envelope is associated with an increase in the fatigue levels of the lower back and upper extremity (Habes **et al**., 1985). When considering the combination effect of load and reach placement distance in one-handed lifting, statistically significant differences in RPE were only evident when ‘light’ loads were transported (Garg and Saxena, 1982). It is therefore hypothesised that subjects required to lift and manoeuvre loads over increasing horizontal reach distances while working under restrictive ceiling heights will experience even greater levels of discomfort than when doing similar tasks in less restrictive environments.

ASSESSING TASK DEMANDS

The discipline of ergonomics assesses and determines the compatibility between the human operator, the industrial task and the working environment (Ayoub, 1992). As each of these three factors is complex, ergonomists are faced with the difficult challenge of estimating the strain that workers experience in the workplace on a daily basis. Due to the multi-faceted nature of the working environment, task assessment tends to be conducted from either a predominantly biomechanical, physiological or psychophysical approach (Ayoub, 1992; Capodaglio **et al**., 1997; Shoaf **et al**., 1997; Dempsey, 1998). The criteria for each of these approaches are diverse, which has resulted in industry receiving conflicting guidelines or recommendations (Dempsey, 1998). Other concerns raised are that scientists tend to conduct investigations employing only one approach (Heacock **et al**., 1997). This can lead to an over, or under, estimation of task demands depending on the approach adopted. Although this is sometimes not feasible, it could lead to injuries if researchers are not aware of these discrepancies. Recognising the implications of this, this investigation was executed in a holistic manner (Charteris **et al**., 1976) although a more detailed emphasis was placed on the physiological approach.

Many of the assessment techniques available such as the NIOSH equation (1993) are applicable to ‘normal’ industrial environments but have limitations when applied to cramped occupational settings. Due to this, limited research has been conducted in these environments. Furthermore, many industries find research time-consuming, expensive and disruptive to the workflow and therefore do not permit the tested individual to leave the task (Allread **et al**., 2000). Thus a further limitation is that most of these studies have been confined to a laboratory environment. Due to the highly controlled nature of the laboratory environment, researchers such as Scott and Renz (2006) highlight the lack of applicability to *in situ* conditions. The laboratory is however important as many extraneous variables can be rigorously controlled thereby enabling researchers to identify the cause of the individual's responses more accurately.

WORKING POSTURE ANALYSIS

As working postures assumed within restrictive environments are difficult to assess, techniques that enable an accurate and valid means of assessing musculoskeletal loading without interfering with task completion are favoured. Methods available include interviews, questionnaires completed after task execution, observational techniques, goniometers, inclinometers, the lumbar motion monitor (LMM), the use of photographs or video analysis, together with potentiometric and flexible electrogoniometers (Capodaglio **et al**., 1997; Li and Buckle, 1999; Vieira and Kumar, 2004).

The most crude measures, which include interviews, questionnaires and observation methods, are best suited to field investigations as the assessment is cost effective and requires minimal interference with task completion. Furthermore, the investigator can observe the task while the individual is completing the job and thereby gain an understanding of the task demands. The recordings can however be influenced by the assessor's personal perspective thereby reducing the reliability of these methods. Furthermore, de Looze **et al**. (1994) contend that observational techniques are not suitable for assessing simulated dynamic physical tasks in a laboratory setting. Moreover, this method is influenced by both intra, and inter, assessor variability and therefore lacks the precision and reproducibility required during thorough investigations (Burdorf **et al**., 1992).

Manual goniometers and inclinometers allow an individual's range of motion within specific body postures to be assessed in two directions during task completion (Gajdosik and Bohannon, 1987; Li and Buckle, 1999). These instruments, although easy to use and relatively inexpensive, tend to be utilised in a clinical or static setting for the determination of joint motion but are unsuitable for use in dynamic movement circumstances (Li and Buckle, 1999). In situations where movement is continuous, electric goniometers are frequently used. This light piece of equipment is adaptable to two-dimensional changes in body posture and the continuous recording of information permits individuals to complete tasks without interruptions. The LMM®, a tri-axial electrogoniometer, is however one of the most frequently employed biomechanical tools. It has been designed as an exoskeleton that mimics the movements of the spinal column (Allread **et al**., 2000; Lavender **et al**., 2006) and in turn provides in-depth continuous information regarding the degree of transverse rotation and sagittal and lateral flexion that occurs during movement. Furthermore, measurements of angular velocity and acceleration are also provided (Ziebath and Noble, 1998; Li and Buckle, 1999; Shin **et al**., 2006). This method, although considered to be the most accurate means of determining the biomechanical strain, is expensive and cumbersome for the worker to wear which can interfere with the individual's responses. Furthermore, the setting up of the LMM is time-consuming and requires attention to detail to minimise error (Li and Buckle, 1999). Moreover, the applicability of this piece of equipment to severely restricted tasks is questionable, as the electrogoniometer may come out of its secure housing in the exoskeleton thereby reducing the accuracy and prolonging the duration of the assessment.

Flexible electrogoniometers, another method of biomechanical strain assessment, are considered favourable as this piece of equipment does not require axis alignment on the joint being investigated yet it is still able to provide reliable information regarding an individual's movement and body posture while completing the task (Vieira and Kumar, 2004). This is especially useful in settings where the accuracy of the assessment might be limited such as within confined spaces where equipment can be dislodged due to body movement within the workspace. Furthermore, as this piece of equipment does not require accuracy in joint placement, it could potentially be used by individuals not qualified as ergonomists to provide a crude measure of the postures adopted during the task.

Although the choice of assessment techniques available is wide, most of these are so scientifically advanced that they are only applicable to a research environment. Furthermore, confined environments are especially demanding when choosing an applicable means of determining task demands due to the spatial restraints. Direct observations of the working postures such as taking photographs are therefore regarded as ideal as this method is simple to use, relatively inexpensive and non-invasive (Vieira and Kumar, 2004). Furthermore, photographs also alleviate the possibility of further restricting the subject. The digital images taken are imported into a software package such as the ErgoImager®, which was the software package utilised in this investigation. This programme allows researchers to import a two-dimensional image and superimpose a mannequin onto the image. The mannequin is then re-orientated and manipulated to mimic the motion present in the image. Information about the individual’s body mass and stature together with task demands such as the load lifted are also entered into the software programme. Thereafter, a crude three-dimensional biomechanical analysis is provided that includes practical information such as the percentage of the population able to work under the task demands, joint moments, shear forces, joint angles and the compression forces experienced through the spinal column. Although this method is recognised as ideal for the assessment of postures in confined spaces, researchers should be aware of its limitations. Even though the mannequin can be orientated to mimic any movement, the programme does not permit the posture of the spinal column to be manipulated therefore the spine cannot be curved to any degree. Additionally, there is a limit to which the angle of other appendages can be orientated. Furthermore, although there is a digital image onto which the mannequin is transposed, small deviations in the exact alignment of the mannequin to the image can occur. It is therefore suggested that this technique is used in combination with other assessment methods when examining task demands in which the focus is an in-depth analysis of the biomechanical strain.

Even though biomechanical assessment is considered essential in determining the stress that the musculoskeletal system experiences during the working day, there are limitations in this method of task assessment. As lifting is a dynamic activity, the use of static biomechanical methods are likely to under-estimate muscular forces as the internal loads imposed by dynamic actions are not taken into account (Ayoub, 1992). Furthermore, many methods do not include the effects of soft tissues in biomechanical strain calculations. Dempsey (1998) also notes that studies done on the spinal column *in vitro* do not necessarily accurately represent what occurs *in vivo* vertebrae which may result in an over, or under, estimation of the biomechanical stress experienced by the individual. These concerns therefore highlight the necessity of adopting a holistic approach to task assessment.

PHYSIOLOGICAL ASSESSMENT

Although assessing physiological responses can be difficult in a confined industrial setting, it is vital to gain an understanding of the extent to which the human operator is taxed as this will affect worker well-being and productivity. As a large percentage of manual industrial tasks are by nature highly repetitive, Ayoub (1992) recommends this means of task assessment as the most reliable.

Heart rate (HR) is frequently utilised to determine cardiovascular strain in the workplace as research has demonstrated that HR is an indication of the individual's physical strain during working periods (Garg **et al**., 1978; Sanders and McCormick, 1992; Bot and Hollander, 2000; McArdle **et al**., 2001). It is also considered to be the easiest, least expensive and most practical means of assessing physiological strain although its application can be limited (Wu and Wang, 2002) due to factors such as climate, gender, level of fatigue and body posture (Nielsen and Meyer, 1987; Bot and Hollander, 2000; Bales **et al**., 2001; McArdle **et al**., 2001; Strath **et al**., 2001; Scott and Christie, 2004), which can cause heart rate responses to alter even though this change is not directly linked to task factors.

Another method of determining physiological strain associated with task completion is to measure oxygen consumption. Oxygen consumption (VO_2), also referred to as pulmonary oxygen uptake, refers to the amount of oxygen that the body can extract and use from the air inspired into the lungs to perform various bodily functions (McArdle **et al**., 2001). At the onset of physical activity and during the initial minutes of exercise, oxygen consumption increases in an exponential manner reaching a ‘steady-state’, if the activity is submaximal, where the amount of energy utilised to power the muscles is equivalent to the amount of ATP produced, after approximately three to four minutes. Inter-individual differences in the time required to reach ‘steady-state’ are determined by training status with trained individuals reaching a ‘steady-state’ more rapidly. However, theoretically, once a ‘steady-state’ has been reached, exercise could continue indefinitely although practically this is dependent on factors such as whether adequate fluid is ingested (McArdle **et al**., 2001). The measurement of oxygen consumption is considered to be a reliable manner in which to predict energy expenditure (EE), as oxygen is required to enable energy to be released.

Direct and indirect calorimeters are usually employed to estimate the degree to which individuals are physiologically strained (McArdle **et al**., 2001). Direct calorimetry, although considered to be the most accurate, requires expensive equipment and isolates the subject from their external environment resulting in appraisals being challenging. Indirect calorimetry, but more specifically open-circuit spirometry, is therefore employed more frequently due to the understanding that the degradation of foodstuffs into energy requires the presence of oxygen (McArdle **et al**., 2001).

Open-circuit spirometry is an easy and inexpensive method of measuring oxygen consumption or energy expenditure. The spirometer calculates the difference between the ambient air (20.93% oxygen, 0.03% carbon dioxide, 79.04% nitrogen) that the individual inhales and the percentage of carbon dioxide and oxygen expired to determine the rate of energy expenditure (Littlewood **et al**., 2002). Two factors namely, the volume of air inhaled and the composition of the expired air, are therefore utilised to measure oxygen consumption and in turn infer energy expenditure. Although this method is considered to be accurate in determining energy expenditure (Duffield **et al**., 2004), it can place additional restrictions on workers already experiencing strain within the working environment due to the additional spatial constraints. Duffy **et al**. (1996) however identify that this method of assessing energy expenditure allows the individual a certain degree of unhindered mobility within the workspace. This method of evaluating energy expenditure can however be cumbersome in already confined environments hence the use of alternative methods of estimating energy expenditure.

Past research has demonstrated that an individualised linear relationship exists between HR and VO_2 responses (Wolfe, 2004; Christie **et al**., 2005). Due to the complexity of assessing physiological responses within the working environment and more specifically restricted environments, researchers have suggested that the individualised relationship between HR and VO_2 for each individual, in each task requiring assessment, should be determined in identical simulated tasks within a highly controlled laboratory setting. This is because of the fact that HR is affected by so many factors such as training status, psychological state and climate (Nielsen and Meyer, 1987; Strath, **et al**., 2001; Strath **et al**., 2002). By utilising this approach, the accuracy of predicting energy expenditure increases (Haskell **et al**., 1993). The physiological strain experienced by the individual *in situ* can then be determined by only recording HR during task completion and inferring VO_2 from the individualised relationship and hence, energy expenditure (Maas **et al**., 1989; Sothmann **et al**., 1991; Sanders and McCormick, 1992; MacKinnon, 1999; Bot and Hollander, 2000; Bales **et al**., 2001; McArdle **et al**., 2001). The individualised regressions would ensure that external factors such as training status are taken into account. Factors affecting HR responses are however still present yet the individualised regressions will ensure that this effect is reduced. The degree of error is however exacerbated as estimations of oxygen consumption are utilised to calculate energy expenditure. Although errors do exist when employing this means of calculating energy expenditure, this technique is especially useful when working in situations where expensive and intricate equipment cannot be used.

Physiological Guidelines for Manual Work

As manual tasks are inherently of a heavy physical nature, several physiological guidelines based on heart rate and oxygen consumption responses, together with energy expenditure levels, have been devised to ensure that workers are not being taxed excessively during the working day (Table IV).

TABLE IV: Physiological guidelines for prolonged manual work.

*(Adapted from American Industrial Hygiene Association (1971), Åstrand and Rodahl (1977) and McArdle **et a**l. (2001).)*

	American Industrial Hygiene Association (1971)		**Åstrand and Rodahl (1977)**	**McArdle et al. (2001)**	
Intensity of Work	**HR** **($bt.min^{-1}$)**	**EE** **($kcal.min^{-1}$)**	**HR** **($bt.min^{-1}$)**	**VO_2** **($ml.kg^{-1}.min^{-1}$)**	**EE** **($kcal.min^{-1}$)**
‘Light’	75 – 100	2.5 – 5.0	< 90	6.1 – 15.2	2.0 – 4.9
‘Moderate’	100 – 125	5.0 – 7.5	90 – 110	15.3 – 22.9	5.0 – 7.4
‘Heavy’	125 - 150	7.5 – 10.0	110 – 130	23.0 – 30.6	7.5 – 9.9
‘Very heavy’	150 – 180	10.0 – 12.5	130 – 150	30.7 – 38.3	10.0 – 12.4
‘Unduly heavy’	>180	> 12.5	150 - 170	≥ 38.4	≥ 12.5

Where: *HR refers to heart rate; VO_2 refers to oxygen consumption; EE refers to energy expenditure.*

Heart Rate Responses

Although physiological guidelines are available, this body of knowledge is limited. The American Industrial Hygiene Association (1971) together with Åstrand and Rodahl (1977) have however provided general information into which heart rate responses are classified into categories ranging from ‘light’ (’75 – 100bt.min^{-1}’ and ‘< 90bt.min^{-1}’ respectively) to ‘extremely heavy’ (‘> 180bt.min^{-1}’ and ‘150 – 170bt.min^{-1}’ respectively) as seen in Table IV. Even though these guidelines are useful for industry to implement, other researchers have provided more specific guidelines. Brouha (1967) argued that workers should maintain an average heart rate of 110bt.min^{-1} over an 8h day although Mital (1984) suggested that male workers maintain heart rates of 99bt.min^{-1}. Snook and Irvine (1969) however provided alternative guidelines depending on whether the task uses predominantly the arm or leg muscles. These authors suggest that when labourers are performing tasks using the legs predominantly, these individuals should not exceed a maximum of 112bt.min^{-1} whereas when completing tasks where the arms are used to a greater degree, heart rate responses should not exceed 99bt.min^{-1}. More recently however, Ayoub and Mital (1989) suggest that workers should not exceed an average HR of 110bt.min^{-1}.

Oxygen Consumption and Energy Expenditure

Oxygen consumption can also be used to determine work intensity and when relativised to an individual’s body mass, can be used to compare individuals. McArdle **et al**. (2001) suggests that a ‘light’ workload utilises between 6.1mlO$_2$.kg^{-1}.min^{-1} and 15.2mlO$_2$.kg^{-1}.min^{-1} during task performance. This increases to between 15.3mlO$_2$.kg^{-1}.min^{-1} and 22.9mlO$_2$.kg^{-1}.min^{-1} during a ‘moderate’ workload. An ‘unduly heavy’ task requires that the human operator uses more than 38.4ml.kg^{-1}.min^{-1} during task performance. Even though other guidelines are available for industry, oxygen consumption is presented in litres per minute which does not allow for comparisons between individuals. Due to the lack of trained personnel in industry who are able to identify when an individual is at risk within the occupational environment it is important that the guidelines are easy to use and interpret otherwise workers will be exposed to tasks where they can be overtaxed, which in turn is associated with decreases in productivity and possible injury.

In order to alleviate confusion, it has been suggested that industry should rather assess whether individuals are overly strained by determining the percentage of maximal oxygen consumption (%VO_{2max}) during work. In the past, guidelines have suggested values ranging from 25%VO_{2max} (Petrofsky and Lind, 1978a; Petrofsky and Lind, 1978b) to 50%VO_{2max} (Åstrand, 1960; Samanta and Chatterjee, 1981; Legg and Pateman, 1985) in an attempt to reduce the extent to which individuals experience fatigue. Brouha (1960) however argues that performing tasks at 50%VO_{2max} are 'fatigue generating' and therefore are not sustainable over extended periods. More recent literature (Legg and Pateman, 1985; Ayoub, 1992; Waters **et al**., 1993; Dempsey, 1998) suggests that executing tasks at 33%VO_{2max} is a more realistic estimate as industrial tasks usually involve both static and dynamic muscular contractions. Although this seems to be a relatively easy manner in which to classify industrial tasks, Wu and Wang (2002) have proposed guidelines linking %VO_{2max} to the duration of the physical task. According to these authors, shifts of four hours in duration can push individuals to work as high as 43.5%VO_{2max} but this decreases to 34%VO_{2max} for an eight hour shift and 31%VO_{2max} during ten hours of physical exertion. Although the percentage of maximal oxygen consumption is one of the most common means of determining physiological workload, authors such as Ayoub (1992) and McArdle **et al**. (2001) have raised concerns regarding the modality of exercise used to assess VO_{2max}. These authors have therefore argued that if the physiological approach is to be employed during task assessment then the %VO_{2max} that workers should be performing at should be determined by testing while individuals are performing the particular lifting task under investigation.

With respect to energy expenditure, workers should expend no more than 5.0kcal.min^{-1} during an 8h shift, which is considered to be equivalent to 33%VO_{2max} for healthy adult males (Dempsey, 1998). Mital (1999) has however taken a more conservative approach and recommended 4.0kcal.min^{-1}, which according to the American Industrial Hygiene Association (1971) and McArdle **et al**. (2001) is considered to be a 'moderate' workload (see Table IV). Although awkward working postures are associated with elevations in energy expenditure, restrictions within the working environment can also increase the energy expended during task performance. According to Gallagher (1999), McPhee (2004) and Chandra Dey **et al**. (2007), mining is the most physically taxing occupation due to its severely restricted working environments and long working shifts of between 10 – 12h. These physical constraints together with task demands results in increases in the degree of physiological strain thereby resulting in an energy expenditure greater than 5.0kcal.min^{-1}. Even though erecting supports within a mine seam to prevent the roof from collapsing expends 5.7kcal.min^{-1} (2736kcal per 8h working day) and shovelling coal requires 7.0kcal.min^{-1} (3360kcal.day^{-1}) according to McArdle **et al**. (2001), both are considered to be 'moderate' workloads.

Despite the level of mechanisation, lifting tasks are also prevalent in the mining industry. In simulated symmetrical lifting and lowering tasks under a lowered ceiling, oxygen consumption and hence energy expenditure was significantly higher in stooped lifting than kneeling lifting (Gallagher, 1991). This finding is supported by more recent research (Gallagher and Hamrick, 1992) where a stooped lifting posture resulted in significantly higher physiological responses than kneeling postures. Furthermore, these authors found that an increase in the elevation of the ceiling had no effect on the physiological cost of lifting. In Kumar **et al**.'s (2000) study, however, subjects lifted a 22kg load to 1.25m under various ceiling heights. Energy expenditure in all three ceiling height conditions were significantly different from one another with subjects utilising the most energy (6.5kcal.min^{-1}) when lifting under a ceiling set at 80% of stature, with the least amount of energy expenditure (5.6kcal.min^{-1}) occurring when lifting under a ceiling located at 90% of stature. Lifting under an unrestricted ceiling height resulted in subjects oxidising 5.8kcal.min^{-1}. Both Gallagher and Hamrick (1992) and Kumar **et al**.'s (2000) findings demonstrate that even if restrictive lifting tasks are similar, the energy expended during task completion is highly variable and frequently unpredictable, leading to confusion in industry.

Subjects performing kneeling lateral lifts under ceilings of 0.91m and 1.02m have been shown to be taxed to a similar degree (Gallagher and Unger, 1990). The same investigation also compared stooped lateral lifting under a 1.12m and 1.22m ceiling height and found that the subjects' responses were comparable. Subjects were however physiologically taxed to a significantly greater degree in the kneeling postures when compared to stooped lifting. It is therefore imperative that industry is able to differentiate between task parameter and hence be able to predict where the energy cost associated with the task is excessive.

OTHER PHYSIOLOGICAL RESPONSES

Breathing Responses During Manual Work

The thoracic cage musculature enables individuals to maintain posture, position their arms and ensure that respiration occurs (Hussain **et al**., 1985) yet when these muscles are employed in activities besides respiration, breathing is affected (Cerny and Ucer, 2004). The process of respiration therefore employs the fewest muscles to reduce the energy cost associated with this physiological function. Three physiological respiratory variables namely, minute ventilation (V_E), tidal volume (V_T) and breathing frequency (F_B), are associated with respiration and are known to change rapidly with the onset of a physical activity (McArdle **et al**., 2001). Minute ventilation (V_E) is the volume of air breathed in each minute and is a product of the rate of breathing (F_B) and an individual's tidal volume (V_T).

During rest (Table V), F_B is usually twelve breaths per minute and V_T is approximately 0.5L.min^{-1}, resulting in a V_E of approximately 6L.min^{-1} (McArdle **et al**., 2001). When increasing the intensity of physical labour, an individual responds by increasing both F_B and V_T (Table V) in different proportions which will ultimately result in an increase in V_E. Cerny and Ucer (2004) found that increasing F_B and V_T resulted in greater energy expenditure due to energy being utilised to move air into the lungs against the forces being produced by the tissues. The depth and rate of breathing is therefore rigorously controlled to reduce these counteracting forces. Other external forces such as restrictive working postures and the use of the arms to perform physical work further increase tissue forces thereby increasing the energy utilised to breathe.

TABLE V: The effect of physical exertion on breathing responses. *(Adapted from McArdle* ***et al****., 2001).*

Condition	**F_B (br.min^{-1})**	**V_T (L)**	**V_E (L.min^{-1})**
At rest	12	0.5	6
Moderate physical activity	30	2.5	75
Vigorous physical activity	50	3.0	150

Where: F_B refers to breathing frequency; V_T refers to tidal volume; V_E refers to minute ventilation

When an individual performs light to moderate activity, initially ventilatory rates increase linearly with oxygen consumption but reach a ‘steady-state’ once the demand for oxygen is equivalent to the amount being received. A linear increase in VO_2 results in a concomitant increase in V_E but this can be attributed to a greater increase in V_T whereas at higher intensities the body relies on a greater increase in breathing frequency (McArdle **et al**., 2001). During strenuous physical work, F_B can increase to approximately 35 – 45br.min^{-1}, however highly trained athletes can breathe at rates of as high as 60 – 70 times per minute during vigorous physical activity (McArdle **et al**., 2001). V_T during vigorous activity can increase to as much as 3.0L.min^{-1}. These increases in V_T and F_B lead to V_E volumes of as great as 100L.min^{-1} or more (Table V). The changes in breathing responses are essential to ensure that the partial pressures of oxygen (pO_2) and carbon dioxide (pCO_2) remain close to the values present during rest (McArdle **et al**., 2001).

Although factors such as physical exertion are known to affect the ratio between V_T and F_B, Cerny and Ucer (2004) identify more specifically that minute ventilation, recorded at an equivalent VO_2, is greater when using the arm muscles then when employing the leg muscles. Breathing frequency was also higher yet the depth of breathing was lower in arm activities. It can therefore be concluded that the use of the arm muscles for physical tasks restricts the movement of the rib cage thereby altering the ventilatory responses to physical activity, resulting in individuals reporting a greater degree of breathlessness with arm work. Individuals using their arms would therefore experience a decrease in work capacity as the ventilatory system would require a greater amount of energy to counteract the effects of using the arm muscles (Harms **et al**., 1997).

Respiratory Quotient

The respiratory quotient (RQ) is a method of determining the substrates oxidised by the body to provide energy during rest and submaximal, aerobic activity (McArdle **et al**., 2001). This is based on the knowledge that there are chemical differences in the structure of carbohydrates, fats and proteins which implies that each substrate requires a different amount of oxygen to complete the degradation of the hydrogen (H_2) and oxygen (O_2) atoms to the end products of carbon dioxide (CO_2) and water (H_2O). The amount of CO_2 produced is therefore an indication of the substrate oxidised (McArdle **et al**., 2001). RQ is consequently determined by dividing the amount of CO_2 produced by the volume of O_2 consumed. During the oxidation of carbohydrates (CHO), the amount of O_2 consumed is the same as the amount of CO_2 produced, which results in an RQ value of approximately 1.00 (McArdle **et al**., 2001). As fats contain more H_2 and carbon (C) atoms than carbohydrates, the ratio between O_2 consumed and CO_2 produced is different. An RQ value of 0.7 therefore indicates that fat is the predominant fuel source being oxidised (McArdle **et al**., 2001). Protein differs from carbohydrates and fats as it is not simply oxidised to CO_2 and H_2O molecules. The protein is first transported to the liver where the amino group is removed and excreted by the body. The last remaining fragment, known as a ketoacid, is then oxidised to CO_2 and H_2O. An RQ of 0.8 signifies that protein is being oxidised predominantly (McArdle **et al.**, 2001).

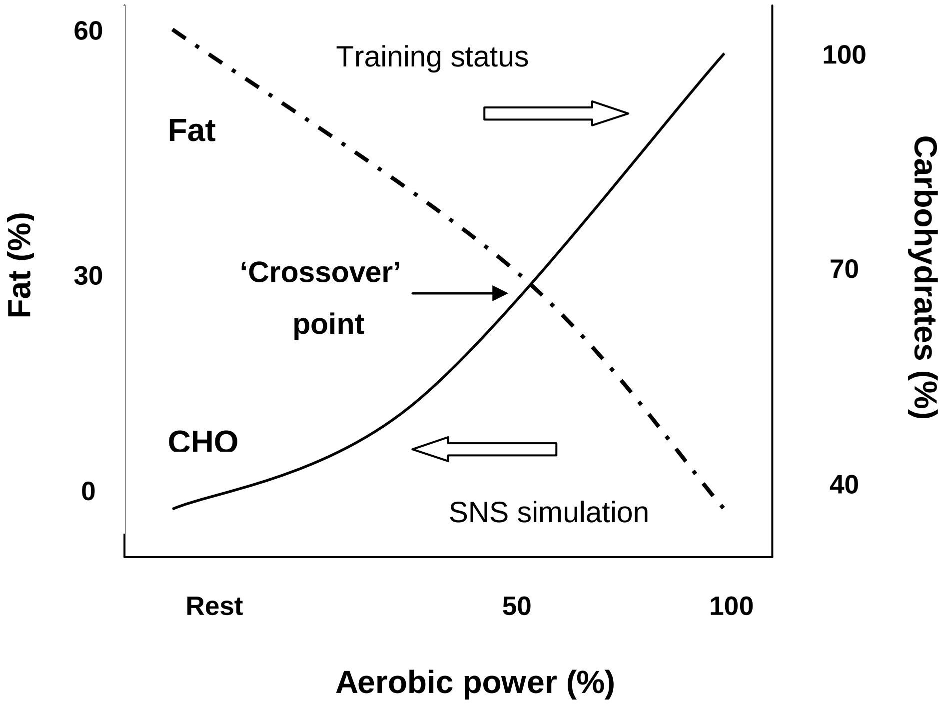


FIGURE 1: Relative energy derived from fat and carbohydrate (CHO) stores relating to aerobic power output.

(Adapted from Brooks and Mercier, 1994).

(SNS refers to sympathetic nervous system; the dotted line refers to fat oxidation; the solid line refers to carbohydrate oxidation).

Although it is relatively simple to determine which substrates are being broken down to provide energy during physical activity, the factors determining which substrates are to be degraded are somewhat more complex. According to Brooks and Mercier (1994), the 'crossover concept' is responsible for deciding which substrate forms the predominant energy source. In order for lipids to be the energy of choice during physical activity, individuals need to be well trained as this ensures that the skeletal muscle tissue has 'retooled' due to a greater concentration of lipolytic enzymes in the mitochondria therefore promoting lipid degradation. Trained individuals also 'crossover' from a predominantly lipid based energy source to one that relies more on carbohydrates at a higher percentage of aerobic power thereby sparing muscle glycogen stores and delaying the onset of fatigue. These individuals also have a dampened sympathetic nervous system response when exposed to the stress of exercise, which in turn promotes the use of lipids and sparing of glycogen stores (Brooks and Mercier, 1994). Exercise intensity also has an effect on substrate utilisation. In Figure 1 it is apparent that at lower exercise intensities lipids are used to a greater extent to provide energy than CHOs, further delaying the onset of fatigue. Carbohydrates are the primary fuel source in untrained individuals, as the muscle tissue has not been provided with a purpose to ‘retool’. Moreover, these individuals release a greater concentration of adrenalin, which is responsible for releasing glucose into the bloodstream and thereby stimulate the utilisation of carbohydrates as a fuel source. Working at a high physical intensity also promotes the utilisation of carbohydrate stores as there is a greater concentration of glycolytic compared to lipolytic enzymes in skeletal muscle. Furthermore at high physical activity levels, the body recruits more fast twitch muscle fibres which rely on glycogen stores for energy (Brooks and Mercier, 1994). The controlled utilisation of energy sources is therefore necessary to delay the onset of fatigue from a physiological perspective.

Although physiological analyses provide an understanding of the events occurring within the body, the manner in which the operator perceives the task is also of equal importance. The psychophysical approach is based on the understanding that the human operator combines feedback from biomechanical and physiological stresses to provide a subjective evaluation of the demands imposed by the task (Ayoub, 1992; Sanders and McCormick, 1992).

SUBJECTIVE TASK ANALYSIS

According to Ekblom and Goldbarg (1971), the subjective evaluation of the degree of physical effort is based on two groups of factors. The perception derived from the muscles and joints are termed ‘local factors’ whereas the demands placed on the cardiovascular and respiratory systems are known as ‘central factors’. Although these two factors seem to be distinctly separate from one another, Robertson (1982) suggests that these perceptual signals are monitored by a multi-factorial mechanism.

Due to the nature of this assessment technique, Legg and Myles (1985) and Ayoub (1992) state that it is essential that subject co-operation and strict experimental control is in place. This will ensure that this approach is extremely effective in determining loads, lifting frequencies or the degree of environmental restriction that the individual can be subjected to over a work shift without enduring cardiovascular, metabolic or subjective feelings of fatigue. Dempsey (1998) however argues that this assessment technique is best utilised in industrial tasks where the frequency of task completion is intermittent in nature. As this investigation was conducted holistically, it was essential to obtain information regarding how the subject perceived the physical tasks. The Rating of Perceived Exertion Scale and The Body Discomfort Map were used to obtain this information.

The Rating of Perceived Exertion Scale

The Rating of Perceived Exertion (RPE) scale (refer to Appendix B) was developed by Borg (1970) and is based on the individual’s perception of their level of exertion during a particular task (Olivier and Scott, 1994). The RPE scale is designed so that the perceptual ratings from 6 to 20 are linearly related to heart rate (Borg, 1978; Sanders and McCormick, 1992). Every alternate number on the scale is linked to a verbal anchor such as ‘very light’ and ‘somewhat hard’ (see Appendix B) in order to make it easier for individuals being tested to make an accurate perception of the intensity of the activity bout (Borg, 1978). Borg (1978) has however cautioned against using this measure to replace an actual heart rate recording as heart rate responses can be affected by factors such as age, the type of activity and environmental conditions. Borg’s RPE scale is however the most versatile as it requires minimal equipment, does not interfere with task completion and is easily learnt and implemented (MacKinnon, 1999). This scale has been validated in a number of activities such as lifting and lowering (Gamberale, 1972; Asfour, 1980), although the results are affected by the individual's previous experience and the level of motivation, as highly motivated individuals tend to underestimate the level of exertion (Sanders and McCormick, 1992). Correlations of between 0.42 and 0.94 have been calculated between HR and RPE in tasks such as lifting and carrying external weights (Robertson, 1982). Garg and Saxena (1982), who investigated lifting tasks with different combinations of load and reach distance, found correlations as low as 0.14. Olivier and Scott (1994) do however caution that although there is a high correlation between heart rate and RPE in most cases, this does not indicate that the two variables are related to one another.

The Body Discomfort Map

Due to the individualised nature of human beings, individuals involved in the same task may experience bodily discomfort in different areas. The Body Discomfort map (see Appendix B) is a modified form of Corlett and Bishop's (1976) Body Discomfort scale and is invaluable to ergonomic investigations as it provides individuals with a manner in which to identify the specific area where discomfort is experienced together with the degree of discomfort experienced. Images of both the anterior and posterior sides of the human body are divided into 28 regions. Subjects are then able to identify the areas of discomfort and describe the extent of discomfort experienced in that region on a scale of 1 ('very light') to 10 ('very uncomfortable').

In a lifting study performed by Kumar and Lechelt (1999), subjects were required to lift a 22kg crate from the floor to a shelf located 125cm above floor level. The load was lifted every ten seconds for a total duration of five minutes. On completion of the lifting protocol, subjects were required to identify areas where the discomfort originated from together with the intensity of the discomfort. Subjects reported discomfort in both the upper and lower extremities. Although discomfort was felt in both of these areas, the intensity of discomfort differed with the upper extremities experiencing a greater degree of discomfort. This is however dependent on the capabilities of the human operator which highlights the importance of assessing the individuals' capacity to perform the task.

WORKER CAPABILITIES

In designing tasks that do not overtax the human operator, the workers' anthropometric dimensions, strength exertion and aerobic capacities are usually the primary foci. However, the ability of these individuals to meet the demands placed on them in the working environment is also determined by each individual's genetic predisposition and environmental factors. It is therefore this interplay that challenges ergonomists to design tasks that can accommodate a substantial proportion of the working population (Das and Sengupta, 1996). Braam **et al**. (1996) further indicates that neglecting to accommodate the human operator when designing industrial tasks can result in health problems, which is further exacerbated when performing in confined spaces.

AGE

Workers tend to reach their physical peak between the ages of 20 and 40yr (McArdle **et al**., 2001). Thereafter, a decline in physical strength (Hyatt **et al**., 1990) and spinal flexibility (Brown **et al**., 1994) is evident. Moreover, the older worker tends to gain weight, which further increases the energy cost of moving loads within the workplace (Godin and Shephard, 1973), and places these individuals at risk of developing chronic diseases such as diabetes, coronary heart disease and arthritis (McArdle **et al**., 2001). The process of aging has also been linked to declines in the execution of both simple and complex movements together with the speed at which these actions are carried out (Shephard 2000; McArdle **et al**., 2001). Aging workers can therefore be considered to be at an increased risk while working especially when performing physically demanding tasks within restrictive environments. In this study, a young student sample was used and as such, age was not a factor.

AEROBIC CAPACITY

Aerobic capacity (VO_{2max}) is a measure of the body's ability to deliver oxygen to the tissues and has been linked to an individual's level of performance (Davies, 1973). This measure of performance is genetically determined by 25 – 40% although an individual's health and training status has also been shown to affect VO_{2max} (McArdle **et al**., 2001). Furthermore, inter-individual differences in the body's capability to utilise oxygen has been linked by Spurr (1987) and McArdle and associates (2001) to the overall mass of skeletal muscle tissue together with the individual's stature and mass.

TABLE VI: Cardiovascular fitness (VO_{2max}) classification for males based on age.

*(Adapted from McArdle **et a**l., 2001).*

	Age (yr)				
VO_{2max} Classification ($ml.kg^{-1}.min^{-1}$)	**≤ 29**	**30 – 39**	**40 – 49**	**50 – 59**	**60 – 69**
Poor	≤ 24.9	≤ 22.9	≤ 19.9	≤ 17.9	≤ 15.9
Fair	25 – 33.9	25 – 30.9	20 – 26.9	18 – 24.9	16 – 22.9
Average	34 – 43.9	31 – 41.9	27 – 38.9	25 – 37.9	23 – 35.9
Good	44 – 52.9	42 – 49.9	39 – 44.9	38 – 42.9	36 – 40.9
Excellent	≥ 53	≥ 50	≥ 45	≥ 43	≥ 41

Even though aerobic capacity is strongly associated with genetics, the level of physical conditioning, health status and age also play a substantial role in dictating an individual's level of performance. Mital **et al**. (1997) and Schibye **et al**. (2001) state that the ability of older individuals to perform heavy manual tasks decreases from the age of 20 years due to changes in aerobic capacity, as is evident in Table VI. More specifically, aerobic capacity decreases progressively at a constant 10% per decade (Shephard, 2000; McArdle **et al**., 2001), resulting in older workers being taxed to a greater degree than their younger counterparts, however, if individuals continue training these decrements can be limited (Dupler and Cortes, 1993; Schibye **et al**., 2001).

SEX

Although both males and females perform manual work, the workforce involved in physical tasks tends to be male dominated. This can be attributed to both historical factors, where women were traditionally expected to work in the home, and the differences in morphology. Males generally have a higher aerobic capacity which can be linked to the substantially larger muscle mass (McArdle **et al**., 2001). This results in males being able to lift heavier loads than females although these differences are most evident in the shoulder region (Miller **et al**., 1993). More specifically, females only have 55% of male upper body strength and 72% of their lower body or leg strength (Knapik, 1997) yet these disparities can vary substantially according to the research of Pheasant (1983). Sex variations are however considered to be the main cause for the greater prevalence of musculoskeletal disorders found in female workers (Gil Coury **et al**., 2002; Dahlberg **et al**., 2004) leading researchers to suggest that female workers should not lift excessive loads especially when working in cramped environments. The present study used only males.

ANTHROPOMETRIC CHARACTERISTICS

Taking into account an individual's anthropometric dimensions can reduce the possibility of developing work related musculoskeletal disorders. In many industrial workplaces, however, there are constraints present causing congestion and forcing workers to adopt awkward postures. Lifting tasks in restrictive conditions demand that the operators engage in a substantial degree of bending and stretching actions. Taller subjects are confined to a greater degree when ceiling heights are lowered, forcing these individuals to adopt a posture in which the trunk is excessively flexed resulting in higher spinal loading. This led Gallagher **et al**. (2001) to conclude that spinal loading is the result of the interaction between the worker's anthropometric dimensions and the restrictive working environment. Furthermore, taller subjects tend to have a longer trunk length, further elevating spinal loading (Splittstoesser **et al**., 2007). These restrictive tasks would therefore be more suited to the shorter members of the working population as these individuals are at a lower risk of developing lower back pain symptoms as they do not the same degree of spinal loading (Wilson and Corlett, 1995; Mital **et al**., 1997). Furthermore, increases in stature are associated with a decrease in work capacity (Farazdaghi and Wohlfart, 2001). As this investigation's main focus was to determine the physiological cost of lifting in restricted environments, stature was limited to reduce the variability of the human operator's responses.

MORPHOLOGICAL CHARACTERISTICS

Body Mass Index (BMI) is frequently used by researchers to determine the normality of an individual's weight and is calculated by dividing the subject's body mass (kg) by their stature squared (McArdle **et al**., 2001). Individuals are considered to be underweight if their BMI is less than $20kg.m^{-2}$, 'normal' weight if they have a BMI between $20kg.m^{-2}$ and $25kg.m^{-2}$ and overweight if they have a BMI > $25kg.m^{-2}$ (Ricardo and Araújo, 2002; Xu **et al**., 2008). The link between an individual's BMI and body fat percentage differs according to ethnic group (Deurenberg **et al**., 1998), which Deurenberg and colleagues (1999) more recently have attributed to differences in body build. Furthermore, clinical studies have demonstrated that increases in BMI are associated with an elevated risk of developing chronic and degenerative conditions such as cardiovascular disease, osteoarthritis and diabetes (McArdle **et al**., 2001; Ricardo and Araújo, 2002).

Work capacity is also affected by BMI with an increase in BMI leading to a linear decrease in work rate production (Ozcelik **et al**., 2004). Decreases in physical work capacity tends to occur in individuals who have a BMI

> 30kg.m^{-2} or < 17kg.m^{-2} (Spurr, 1987; Desai **et al**., 1984; Reybrouck **et al**., 1997; Strickland, 2002). Poor work capacity in obese individuals in particular has been suggested to be attributed to decreases in Type I fast twitch fibres and increases in the prevalence of Type II slow twitch fibres (Kissebah and Krakower, 1994) resulting in these individuals being more prone to developing exhaustion during physically taxing tasks as Type I fibres are generally considered ‘fatigue-resistant’.

STRENGTH

According to Mital and Kumar (1998), the assessment of an individual’s strength is an important determinant of the human operator’s physical capabilities to perform manual work. Strength exertion is however affected by the design of the workspace and the posture adopted by workers (Haslegrave **et al**., 1997), with poor industrial workspace layout resulting in workers adopting awkward postures, reducing strength expression (Kumar and Garand, 1992; Kumar, 1994). According to Chaffin **et al**. (1983) even minor constraints in the working environment can lead to substantial decreases in strength exertion. Strength exertion is affected more specifically by the interaction between the adopted posture, the horizontal reach distance and the orientation of the worker’s arms (Mital and Kumar, 1998). In tasks such as lifting, incompatibility between the worker’s strength and task demands can lead to individuals working at a greater percentage of their maximal capacity thereby overloading the musculoskeletal system and increasing the possibility of developing musculoskeletal disorders (MSDs).

In general, males form the basis of the heavy manual workforce as these individuals are able to exert a greater degree of force (McArdle **et al**., 2001). Furthermore, males have a greater degree of upper body strength (Clarke, 1986; Dahlberg **et al**., 2004) although strength declines occur earlier than females (McArdle **et al**., 2001). In contrast, Larsson **et al**. (1979) found that male upper body strength remains relatively unchanged until age 50 but leg strength declines earlier in this population group. As males are generally more robust than females, young healthy male students were recruited for this study.

THE SOUTH AFRICAN WORKFORCE

The South African manual workforce is plagued by a various problems. Due to the Apartheid regime of the past, many of these individuals are poorly educated and therefore are not able to gain employment that would result in adequate remuneration. Hence, many of these workers are living in impoverished communities where housing and sanitation are frequently overlooked (Christie, 2002). Furthermore, the low incomes are associated with a diet deficient in energy rich food rendering many of these labourers unable to perform at their optimum. Moreover, a substantial percentage of these individuals are covering long distances on foot before even arriving at the workplace (Christie, 2002) further reducing their ability to perform.

Even though a large proportion of human operators are faced with inadequate nutrition on a daily basis, many others are migrating to urban areas where their earning potential is rising. This has led to migrants ingesting diets with a greater proportion of dietary fats, animal protein, vitamins and minerals together with a reduction in carbohydrate intake (Bourne **et al**., 2002; Vorster **et al**., 2005). Thus this rural/urban transition is culminating in more individuals adopting a more Westernised diet which is associated with being overweight and obesity. In the past, the less affluent members of the workforce regarded obesity as an indication of wealth (Strickland, 2002) which in some cases is continuing into the workforce of today. This phenomenon is however associated with an increase in the prevalence of non-communicable diseases such as diabetes and coronary heart diseases (Bourne **et al**., 2002). Although at present coronary heart disease is still uncommon in individuals employed as manual labourers, this trend is predicted to change with the increased urbanisation (Kruger **et al**., 2003). It is therefore evident that South African workers are exposed to many often unconsidered factors which in turn impact their performance within the working environment especially when environmental conditions are constrained.

CONCLUSION

Manual tasks are by their very nature complex, with various factors influencing the performance of these activities. As there is an interaction between the task, the worker and the environment, it is essential to ensure that researchers adopt a predominantly holistic approach to task assessment as this will ensure that the numerous factors affecting the individual are taken into account (Charteris **et al**., 1976; Dempsey, 1998). Lifting tasks performed within restrictive settings where the manual labourer is required to move loads over varying distances are especially complex due to the interaction of these factors. This study therefore investigated the impact of confined spaces and increasing reach distances on the human operator’s postural, physiological and perceptual responses with a specific emphasis being placed on the energy cost of working within these environments.

CHAPTER III

METHODOLOGY

INTRODUCTION

Although a considerable amount of research has been conducted on lifting over the years, where factors such as load, frequency and task duration have been investigated, there is a lack of information available regarding the impact of ceiling restrictions and different lifting placement positions on worker responses. According to Kumar (1999) lifting loads in congested working environments is commonplace in industries around the world with many of these tasks requiring that the work be performed under a lowered ceiling. Work performed within these constraints includes industries such as mines, aircraft luggage stowing and the packing and warehousing industries (Gallagher and Unger, 1990; Gallagher and Hamrick, 1992; Rückert **et al**., 1992; Gallagher **et al**., 1994; Gallagher, 2005).

A common activity observed in these industries, is the task of lifting and lowering objects. With lifting generally, workers adopt a variety of postures, including squatting, stooping or a combination of both. Individuals in restricted environments adopt similar postures depending on the degree of restriction; although, if the restriction is severe, these workers are forced into completing their jobs while kneeling or lying down. Due to the highly individualised nature of each worker’s lifting technique, the type and degree of stress experienced within the workplace will differ (Gallagher and Unger, 1990; Gallagher and Hamrick, 1992; Rückert **et al**., 1992; Gallagher **et al**., 1994; Gallagher, 2005). If excessive reach demands are added to these environmental demands, the stresses placed on the individual will be further exacerbated (Sengupta and

Das, 2004). Due to the relative lack of information regarding how individuals respond to the interaction of lowered ceiling height and excessive reach demands, this investigation was undertaken to address this.

PILOT STUDIES

Several pilot studies were conducted in the Ergonomics Laboratory located in the Department of Human Kinetics and Ergonomics at Rhodes University prior to the commencement of the final experimental sessions. These pilot investigations were conducted on three male subjects in order to gain an understanding of the manner in which these individuals responded to changes within the simulated working environment. Additionally, pilot subjects were exposed to different task durations while working in confined spaces to determine when the volume of oxygen inhaled was equivalent to the oxygen consumption. Pilot studies also enabled the researcher to determine the most practical manner in which to conduct the investigation.

EXPERIMENTAL DESIGN

As this investigation focused specifically on the impact of ceiling restrictions and the reach demands of load placement on lifting capability, the load was kept at a relatively ‘light’ 12kg, which is within both the International Labour Organisation’s (1962) and the National Institute of Occupational Safety and Health’s (1981) recommendations, and its dimensions were standardised across all the conditions. This ensured that subjects would not be excessively taxed and the impact of the independent variables would be evident in the subjects’ responses. Lifting frequency was maintained at 6lifts.min^{-1}, which is considered to be ‘optimal’ under ‘ideal’ lifting conditions (Mital **et al**., 1997). The ceiling height was restricted to 1460mm (76 – 80% of the sample’s stature) to force subjects to adopt an awkward working posture yet also reduce the possibility of musculoskeletal complaints as subjects were drawn from a student population and therefore not trained in industrial lifting tasks. Although other studies (Gallagher and Unger, 1990; Gallagher and Hamrick, 1992; Rückert **et al**., 1992; Korkmaz **et al**., 2006) have investigated considerably lower ceiling heights, Gallagher **et al**. (2001) states that regardless of the extent to which the ceiling is lowered, subjects responses will still be affected. In 2005 Gallagher argued that the energy cost is directly related to the interaction between the specific posture adopted and the task performed. Subjects were therefore encouraged to adopt a ‘free style’ lifting technique to enable the researcher to gain an understanding of the manner in which task constraints affect working postures. A further task constraint consisting of a barrier of 554mm (102 – 111% of knee height) placed in front of the load simulating the presence of an industrial bin was also added, many of which are evident in industrial settings (McKean and Potvin, 2001; Budihardjo and Derrick, 2004). The impact of lifting a load over a barrier and placing it either 400mm or 800mm from its starting position while working in both restricted and unrestricted conditions was investigated.

TABLE VII: The four different lifting conditions.

Condition	Environmental Constraint	Horizontal Distance Moved
Unrestricted (URN)	None	400mm
Restricted (RN)	Lowered ceiling height (1460mm)	400mm
Unrestricted (URF)	None	800mm
Restricted (RF)	Lowered ceiling height (1460mm)	800mm

Four different conditions were therefore examined (Table VII) which included combinations of ceiling restriction and reach distance. These included lifting the load over a barrier and placing it close to its origin (400mm distance) in a restricted environment (RN), performing the same task while in an unrestricted environment (URN), lifting the load over a barrier and placing it far from its origin (800mm distance) in a restricted environment (RF) and lifting a load over the barrier to place it far from its origin while performing in an unrestricted environment (URF). The duration of the task was limited to six minutes per condition to enable a physiological ‘steady-state’, if applicable, while minimising the stress placed on the student volunteers. Due to logistical reasons, subjects either completed both restricted or both unrestricted conditions on the testing day.

MEASUREMENTS AND EQUIPMENT PROTOCOL

Prior to the investigation, basic demographic and anthropometric data were collected on all of the participants. This included measures of age, stature, body mass and grip strength.

ANTHROPOMETRIC AND STRENGTH MEASURES

Each subject’s stature and body mass were recorded as these factors are known to affect the development of musculoskeletal disorders (Rückert **et al**., 1992), and the energy cost of task performance (McArdle **et al**., 2001).

Stature – Harpenden® Stadiometer

Stature was measured from the vertex in the mid-sagittal plane to the floor. Subjects were required to stand erect and barefoot on the base of the Harpenden® stadiometer with the visual axis parallel to the surface of the floor. The individual’s stature was then recorded in millimetres. Stature was delimited to a range of 1750mm to 1900mm to ensure that subjects were being equally restricted.

Body Mass – Toledo® Scale

Oxygen consumption and therefore energy expenditure are directly related to an individual’s body mass (McArdle **et al**., 2001). In order for comparisons to be made between subjects some of the relevant responses were relativised to body mass. Body mass was recorded to the nearest 0.1kg using a previously calibrated TOLEDO® scale. Subjects were required to stand stationary in minimal clothing with their weight equally distributed over both feet while body mass was recorded manually.

WORKING POSTURE ANALYSES

Assessing working postures assists in determining the strain placed on the human operator while completing tasks (Vieira and Kumar, 2004). Furthermore with the prevalence of restrictive working environments in industry, the assessment of the working posture adopted during task performance was hypothesised to provide valuable insight into how workers adapt to external constraints.

Digital Images – Kodak® Digital Camera

Analyses of the postures adopted during the testing session were accomplished with the use of a digital camera, which was set up on a tripod at 90 degrees to the task. Three images of the manner in which the subjects lifted the load and adapted to the constraint were taken at the initiation of the lift, while the load was being held and while the load was lowered over the barrier. The images were taken in the third and last minute during the testing session to determine whether task parameters had influenced the posture adopted.

A sample of the working postures captured during the lifting tasks were analysed using the ErgoImager® programme (NexGen Ergonomics). This programme, although theoretical, takes into account the individual's anthropometry and the load supported by the hands, while providing basic information regarding the percentage of the population able to complete the task, lower back compression forces and whether the posture is balanced.

PHYSIOLOGICAL ANALYSES

Physiological measurements have been shown to provide an accurate reflection of how taxing the task is on the individual (Rückert **et al**., 1992; Sanders and McCormick, 1993; McArdle **et al**., 2001).

Heart Rate – Polar® S410 Heart Rate Monitor

A Polar® S410 Heart Rate monitor was used to record cardiac responses during task performance. An electrode strap was placed around the mid-chest at the inferior border of the pectoralis major muscle, in line with the apex of the left ventricle (Figure 2). The electrode is responsible for detecting the electrical activity of the heart, which is reflected as a heart rate displayed on a wristwatch. Contact between the skin and electrode strap is essential and was achieved by moistening the strap with water. The wrist watch was located close to the subject to ensure that transmission between the two units was optimal yet the wrist watch was kept out of the subject’s line of sight as heart rate responses can be affected by an individual’s psychological responses (McArdle **et al**., 2001). ‘Reference’, ‘working’ and ‘recovery’ heart rate responses were recorded to gain insight into the manner in which the task taxed the cardiovascular system and to ensure recovery between conditions.

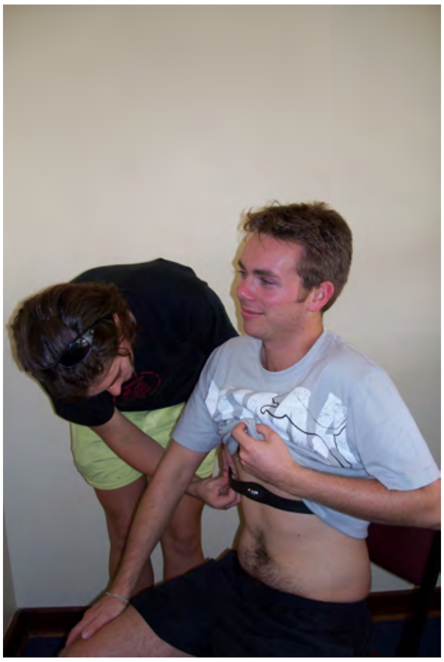


FIGURE 2: **A heart rate monitor being attached to the subject.**

Portable Ergospirometer – Cosmed K4b$^{2®}$

A portable and lightweight ergospirometer, the Cosmed K4b$^{2®}$ was used to quantify the physiological work demands on a breath-by-breath basis. More specifically, measures of breathing frequency (F_B), tidal volume (V_T), minute ventilation (V_E), oxygen consumption (VO_2), carbon dioxide production (VCO_2) and respiratory quotient (RQ) were measured. Energy expenditure (EE) was determined from the VO_2 and RQ measures.

The system consists of a base unit, telemetric unit, calibration unit, a portable unit attached to the subject and a facemask (Littlewood **et al.**, 2002). Prior to testing subjects, the Cosmed K4b$^{2®}$ was switched on for a minimum of forty-five minutes before calibration commenced. Calibration was performed using ambient air within the laboratory and with known concentrations of oxygen (16.10%) and carbon dioxide (5.03%) gas obtained from a gas cylinder. The volume of air passing through the mask was calibrated through the use of a 3L calibration syringe. A further calibration occurred immediately prior to initiating the testing bout during which the Cosmed K4b$^{2®}$ was calibrated to ambient air for a second time.

FIGURE 3: An assistant attaching the Cosmed K4b$^{2®}$ to a recruited subject.

Prior to testing, the facemask was attached securely and comfortably over the subject’s nose and mouth using a mesh head cap (Figure 3) while the portable unit was attached to the subject’s back. Air movement occurs continuously through the mask due to a low resistance bidirectional turbine located in the mouthpiece of the mask. The volume of oxygen inhaled and carbon dioxide exhaled were analysed via gas analysers located within the mouthpiece of the mask. Due to the sensitivity of these gas analysers, accuracy is within a range of < 0.01 - 100% with a response time of less than 120 milliseconds. This information was then transferred to a portable computer through a telemetric unit enabling the data to be viewed after every breath.

PERCEPTUAL ANALYSES

Due to the multidisciplinary nature of ergonomics, this investigation used various perceptive scales to determine how taxing the subjects perceived the physical tasks to be.

The Rating of Perceived Exertion Scale

In order to obtain a measure of how taxing an individual perceives a specific task to be, Borg (1970) developed the Rating of Perceived Exertion (RPE) scale (refer to Appendix B). The scale ranges from ‘6’ to ‘20’ with verbal anchors ranging from ‘very, very light’ to ‘very, very hard’. These anchors enable individuals to accurately determine the extent to which the body is taxed. The premise behind the scale is that the number chosen when multiplied by 10 would provide an indication of heart rate responses during the task. Due to the nature of this method of evaluation, it is paramount that subjects are fully informed as to the manner in which the scale is to be used in order to ensure that valid individual responses are obtained.

During this investigation the sample group were required to provide information as to the extent to which they perceived that their cardiorespiratory system, otherwise referred to as ‘central’ RPE and musculoskeletal system, otherwise referred to as ‘local’ RPE were taxed during task performance.

Body Discomfort Map

The Body Discomfort Map (see Appendix B), modified from Corlett and Bishop’s (1976) Body Discomfort scale, was employed to enable the investigator to gain a more holistic view on the effect that the different combinations of ceiling restriction and reach had on the subject’s musculoskeletal system. The Body Discomfort map is an illustration of 27 different segments located on the anterior and posterior sides of the human body. A scale rating the level of discomfort from 1 (very slight discomfort) to 10 (extremely uncomfortable) was provided to enable subjects to provide an indication of the level of discomfort experienced. After the lifting task had been completed, each subject was required to identify a maximum of three areas where discomfort could be felt and then to rate the intensity of the discomfort on a scale of 1 (very slight discomfort) to 10 (extremely uncomfortable).

SUBJECTS

SUBJECT CHARACTERISTICS

A sample of 32 male subjects ranging in age from 19 – 27yr volunteered for this study. All subjects were considered healthy and were enrolled as students at Rhodes University. Although subjects were physically active, none were trained in industrial lifting tasks. Furthermore, subjects reported that they had no history of lower back or upper body injuries in the six months prior to the commencement of testing. The subject's characteristics are summarised in Table VIII. Subjects volunteering for this investigation were only Caucasian.

TABLE VIII: Characteristics of the subjects (N = 32).

	Mean	**SD**	**CV (%)**
Age (yr)	21.55	1.92	8.91
Stature (mm)	1810	0.04	0.002
Body mass (kg)	79.88	10.47	13.11
BMI (kg.m^{-2})	24.21	2.67	11.03

Where: SD refers to standard deviation; CV refers to co-efficient of variation; BMI refers to Body Mass Index

Although age is known to vary in industry, this investigation only recruited individuals between the ages of 19 and 27 years (21.55 ± 1.92yr). This sample was chosen as research has demonstrated that the vertebral column is able to withstand compression forces of up to 7500N (Jager **et al**., 1991) and these individuals tend to have a greater resistance to the development of musculoskeletal disorders due to muscle tissue having reached its greatest cross sectional area (McArdle **et al.**, 2001). Subjects recruited for this study had a mean body mass of 79.88kg (Table VIII) and although not experienced in restrictive tasks, the subjects were healthy and within the ‘normal’ BMI range (24.21 ± 2.67kg.m^{-2}).

EXPERIMENTAL PROCEDURES

PRE-TESTING/HABITUATION

All subjects were required to attend a practice session of approximately an hour in duration during which a full explanation of all the lifting tasks (Appendix A), the equipment to be used and the responses that would be recorded were given. Furthermore, subjects were instructed on which activities to refrain from in the twenty-four hour period prior to testing (Appendix A). Subjects were encouraged to ask questions during this session. A letter of information detailing the full extent of the test procedures together with any risks, or benefits that could be gained from the testing was then provided (Appendix A). Subjects were also reassured that there was no obligation to continue participating in the study and that testing could be terminated at any stage. If subjects were still willing to participate, a letter of informed consent was signed before any testing procedures were initiated (Appendix A).

The consenting sample group were then weighed and their stature recorded. Subjects were also requested to disclose whether they had experienced any upper body or lower back injuries within the preceding 6-month period. As none of the subjects had prior experience in industrial lifting tasks, a lifting familiarisation session followed where subjects practised lifting the 12kg load within each of the four conditions at a frequency of 6lifts.min^{-1} for a minimum of three lifts.

EXPERIMENTAL SESSION

Subjects were instructed to refrain from ingesting alcohol, being involved in strenuous activities or ingesting medication in the twenty-four hours preceding the testing session (Appendix A). Subjects were also reminded to ingest a light meal at least two hours prior to testing. On the day of testing, two subjects were required to come to the testing centre in the Department of Human Kinetics and Ergonomics at Rhodes University.

On arrival, the testing procedures were reviewed and subjects were encouraged to ask questions regarding the test protocol, equipment and the measurements to be taken before any equipment was attached to the individual. Subjects were also informed of which lifting protocols would be performed during the test session and the order in which they would be performed. The electrode strap of the heart rate monitor was attached around the subject’s chest and the subject was then required to remain seated while the mask of Cosmed K4b$^{2®}$ was being attached over the subject’s nose and mouth via a skullcap. The harness of the Cosmed K4b$^{2®}$ was then attached to the subject’s back and the portable unit from the Cosmed K4b$^{2®}$ was positioned in the harness. Once all the equipment had been attached to the subject and the final calibration for the Cosmed K4b$^{2®}$ had been completed, the subject was required to remain quietly seated for two minutes while ‘reference’ physiological data (HR, breathing variables, VO_2, VCO_2, RQ and EE) was recorded both electronically and manually. This information was used as a baseline with which to compare the responses recorded during the testing sessions.

Once two minutes of resting data had been recorded, the individual was then required to commence the lifting protocol. Subjects either performed both of the restricted (restricted 400mm and restricted 800mm) or both of the unrestricted (unrestricted 400mm and unrestricted 800mm) conditions during the testing sessions (Figure 5). Due to logistical constraints, subjects either completed both restricted or both unrestricted lifting conditions. Subjects were required to start each lift behind a ‘starting line’ located 755mm away from the barrier. The lifting task required that subjects lift a 12kg load, located in a demarcated area of 480mm wide and 640mm long in front of a barrier, over the barrier of 554mm once every ten seconds for six minutes. The load was then placed either 400mm or 800mm away from the load’s initial position, which was demarcated by coloured tape located on the floor (Figure 4).

On the sound of a computer-generated buzzer, the subject took a step forward from behind the ‘starting line’, grasped and lifted the load over the barrier and placed it at the correct distance away from its initial position. The subject then returned to behind the ‘starting line’ and waited for the next buzzer to be sounded while an assistant replaced the load into its demarcated area in front of the barrier. Subjects were asked to identify the extent to which they perceived the task to be taxing from both a cardiorespiratory (‘central’ RPE) and a musculoskeletal (‘local’ RPE) perspective by pointing at the Rating of Perceived Exertion Scale at the end of the first three-minute period and once again at the end of each lifting condition. Digital images of the posture that the subjects assumed during the lifting tasks were taken to determine the manner in which the task constraints affected the posture adopted.

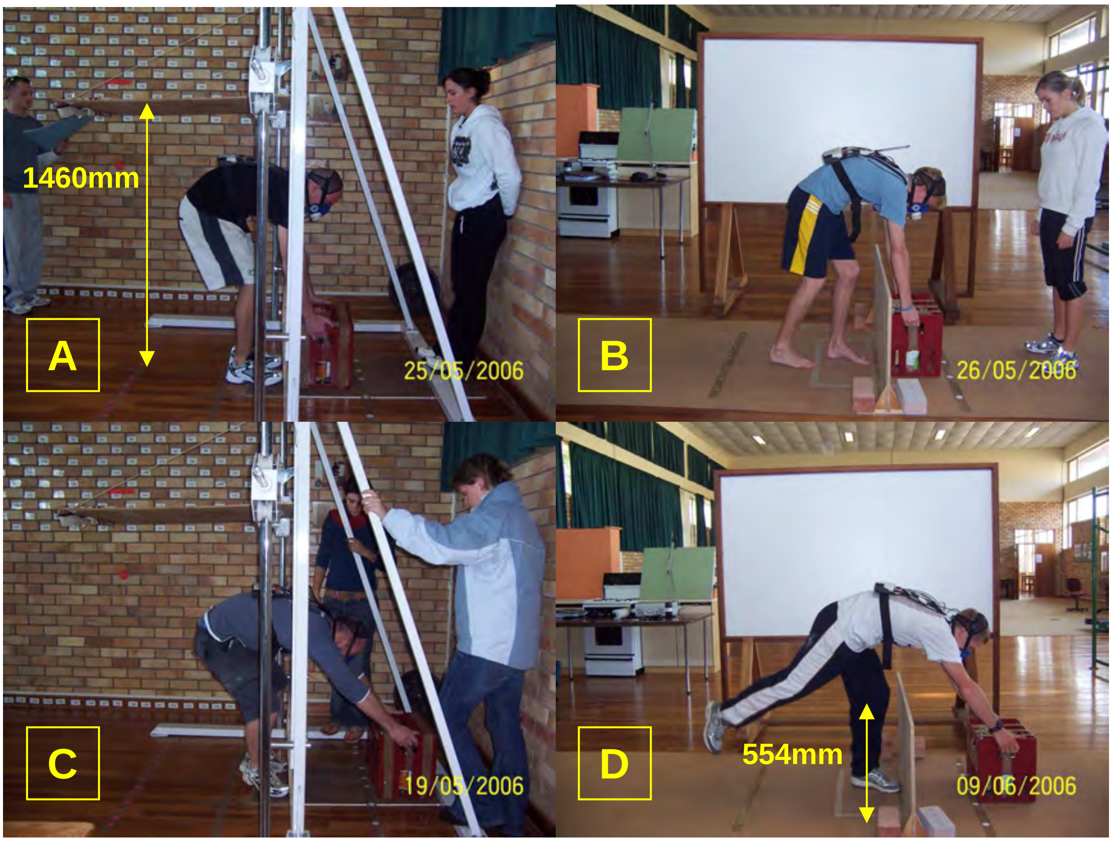


FIGURE 4: **Conditions (A): restricted lift, (B): unrestricted lift with a reach of 400mm and conditions (C): restricted and (D): unrestricted with a reach of 800mm.**

On completion of the lifting task, subjects were once again asked to take a seated position and rest until heart rate responses were within 10bt.min^{-1} of their 'reference' heart rate. During this period subjects were also asked to identify, by pointing to the Body Discomfort Map (Figure 5), the three regions where they experienced the most discomfort and then rate the degree of discomfort experienced in that specific area. The second subject then commenced the testing procedure while the first subject was recuperating.

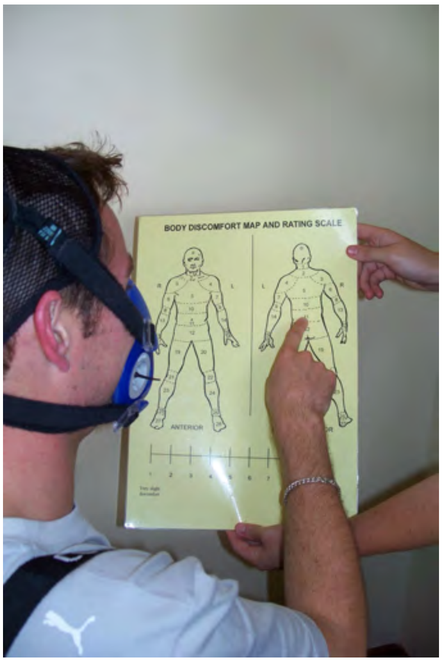


FIGURE 5: **Subject identifying areas of discomfort after completing the lifting task**

STATISTICAL ANALYSIS

All data were analysed using STATISTICA (version 7.0) statistical software and basic descriptive statistics were run on all the variables. A significance level of 0.05 was selected to reduce the possibility of a Type I error occurring to five chances in every hundred responses. Although the possibility of a Type I error occurring was reduced to 5%, the possibility of committing a Type II error (failure to reject a false hypothesis) is dependent on the size of the sample. Thirty-two subjects were recruited for this investigation decreasing the possibility of committing a Type II error.

In order to determine whether physiological ‘steady-state’ had been reached, related student t-tests were run on the data collected during the third and sixth minutes. Furthermore, a one-way repeated measures analysis of variance (ANOVA) was performed on the mean of the data collected in the last four minutes of the task to investigate whether a statistically significant difference was present between the various lifting conditions. A Tukey test was utilised for post hoc analyses. Two-way ANOVAs were conducted on the data collected in the sixth minute of lifting to determine the overall effects of ceiling height and reach distance together with the combination of the two factors. Lastly, linear regressions were constructed to examine whether a relationship existed between HR and VO_2 responses.

CHAPTER IV

RESULTS AND DISCUSSION

INTRODUCTION

Lifting activities are prevalent around the world with many of these tasks being performed in confined occupational environments (Kumar, 1999). Individuals working within confined environments such as the mining, aircraft baggage stowing, warehousing and packaging industries (Gallagher and Hamrick, 1992; Rückert **et al**., 1992; Gallagher, 2005; St-Vincent **et al**., 2005; Splittstoesser **et al**., 2007) are often required to adopt awkward postures in order to complete the task. This is associated with increased spinal loading together with elevated energy expenditure and perceptions of fatigue (Gallagher, 2005). Due to the difficulties associated with working within these environments, assessment of these tasks is challenging. This is largely due to the inability to access these areas with often bulky and cumbersome equipment which is likely to interfere with normal work practices. Furthermore, most of the equipment is expensive hence limiting *in situ* studies. This investigation was therefore a laboratory study that assessed the postural demands, physiological cost and the subject's perception of lifting and lowering a load during four conditions with varying combinations of ceiling height and load placement distance.

POSTURAL ANALYSES

When human operators are required to perform in restricted spaces, they tend to be exposed to a substantial degree of unnecessary strain. Due to the holistic nature of this investigation, a crude analysis of the manner in which the environmental constraints influenced the orientation of the body was conducted. According to authors such as Haslegrave (1994), Vieira and Kumar (2004) and Gallagher (2005), the posture adopted is intrinsically linked to the interaction between task demands and the space available to execute the task.

COMPARISON OF RESTRICTED AND UNRESTRICTED CONDITIONS

As the working postures adopted by the subjects were similar, only one image from each condition was utilised for the postural analysis. In addition, only one subject was used to eliminate the effects of stature and lifting technique. It is therefore obvious that statistical analyses were not conducted. Furthermore, due to the limitations associated with the ErgoImager® when superimposing and orientating the mannequin onto the digital image, the position of the shoulder and hips were always correctly aligned to ensure that as far as possible an accurate prediction of forces could be obtained.

Lift Initiation

Although past research has reported that the magnitude of the confinement affects the posture adopted during task completion, subjects in both the restricted and unrestricted tasks assumed a semi-squat posture (Figure 6).

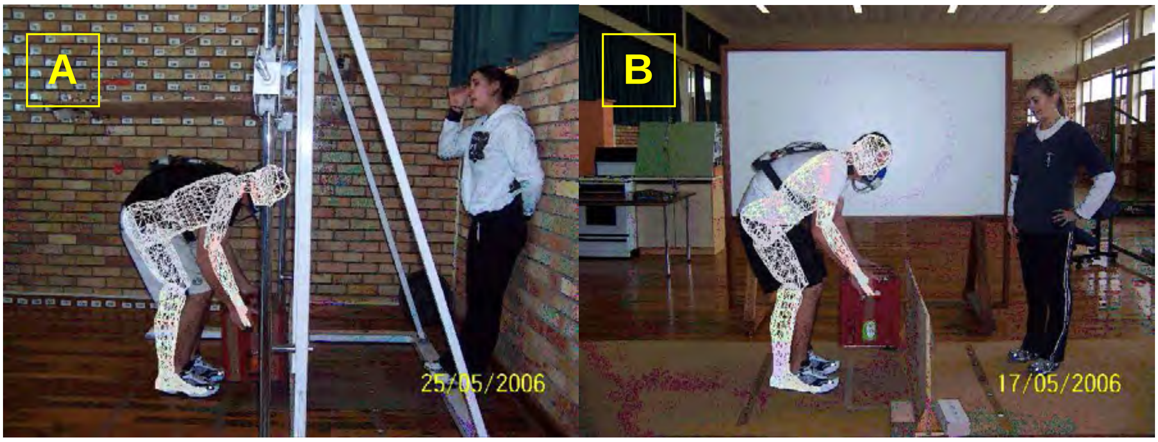


FIGURE 6: Comparison of lifting postures adopted in the (A) the restricted and (B) the unrestricted conditions.

TABLE IX: Forces (N) in the L_5/S_1 joint during lift initiation.

Joint	Force (N)	Restricted lifting	Unrestricted lifting
L_5/S_1	Compression	3061	2611
	Shearing	326	337

The stresses placed on the spine during the two different conditions are shown in Table IX with greater compression forces evident in the restricted condition which supports the findings of Rückert and associates (1992) and Kumar (1999). More specifically in the current investigation, compression forces during lift initiation in the restricted condition (3061N) were 90% of the recommended limit of 3400N (NIOSH, 1981). According to NIOSH (1981), forces over this limit place individuals older than 40yr at a high risk of developing microfractures in the vertebral end plate if exposed to these conditions for extended periods. Even though individuals in this investigation were young and not exposed to loads such as these on an everyday basis, it is hypothesised that the cumulative effect over many years could contribute to the possibility of developing musculoskeletal conditions such as lower back pain. Although it is acknowledged that the compression forces in the unrestricted condition (2611N) were below the 3400N limit, the human operator is still exposed to loads which are 77% of the limit, suggesting that even working in the unrestricted conditions places excessive strain on the human operator. Shearing forces should not exceed 1000N (McGill, 1996) during lifting tasks. It is evident from Table IX that the shearing forces during lift initiation in both the restricted (326N) and unrestricted (337N) were similar and were well below the suggested limit. These findings agree with the work of Splittstoesser **et al**. (2007) who reports that the highest degree of spinal loading occurs during lift initiation regardless of the height of the ceiling.

Load Lifting

The lifting postures adopted during the load lifting period (over the barrier) of the task are seen in Figure 7. As is evident while lifting in the restricted environment (A), the subject adopts a more flexed posture in order to move within the environment while in turn reducing the severity of the compression forces (Table X). Furthermore, the chin is tucked into the chest to prevent the head from coming into contact with the ceiling.

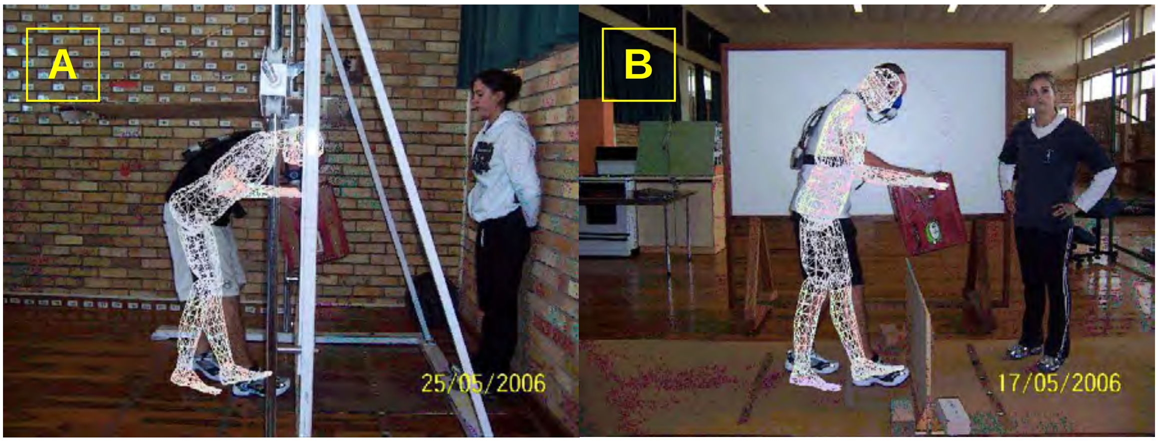


FIGURE 7: Lifting postures adopted during the lifting action in (A) the restricted and (B) the unrestricted tasks.

During load lifting, compression forces in L_5/S_1 were higher in the unrestricted (2257N) than the restricted (1182N) condition (Table X). It would have been expected that the more forward flexed posture (Figure 7A) would result in higher compression forces as reported by Rückert **et al**. (1992) and Elfeituri (2001). However, in Figure 7(B), the subject was more upright in posture and the load further from the spinal column which increases the distance from the fulcrum and hence the compression forces experienced in the spine. Thus, in this analysis the fact that the load was further from the COM created greater compression forces than the posture adopted in the restricted task where the load could be kept closer to the individual's COM. Hence, these findings suggest that when assessing the impact of ceiling restriction, the placement of the load has quite a big impact on the strain experienced. This also highlights the complexity of human centred research where each individual adopts different techniques to accomplish tasks.

With regards to shearing forces, while lifting during the unrestricted task there were greater shearing forces (396N) compared to restrictive lifting (360N). This was an unexpected finding as a greater degree of trunk flexion is seen in the restricted condition (Figure 7), which is usually associated with higher shearing forces. Possible reasons for this finding is that the subject held the load closer to the COM during restricted lifting thereby reducing shearing forces.

TABLE X: Compression and shearing forces (N) during load lifting.

Joint	Force (N)	Restricted lifting	Unrestricted lifting
L_5/S_1	Compression	1182	2257
	Shearing	360	396

Load Lowering

The posture adopted during load lowering was similar in both the awkward and 'normal' lifting tasks (Figure 8).

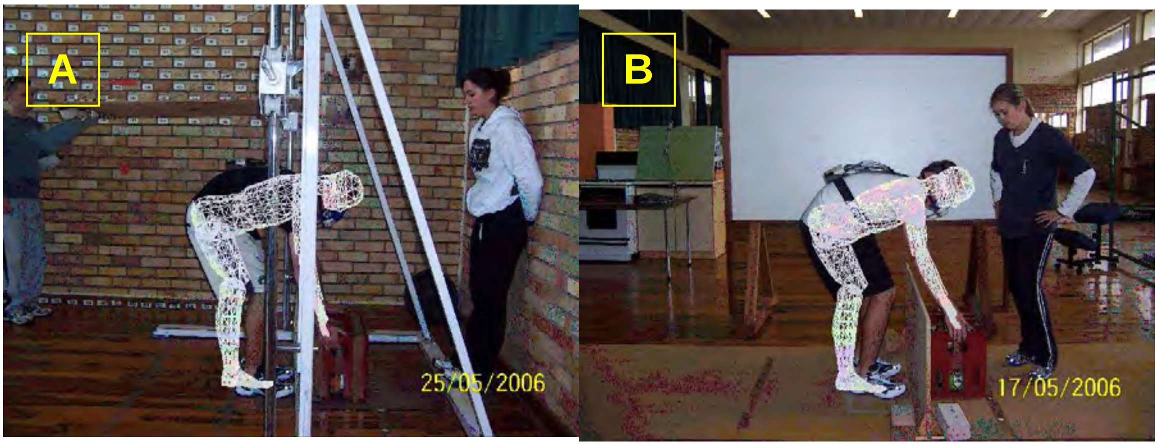


FIGURE 8: The lowering posture adopted during (A) the confined and (B) the unconfined lifting tasks.

Due to the load being placed over the barrier, the subject employed a similarly 'hunched' posture in both conditions in order to place the load accurately. The degree of strain experienced in the unrestricted and restricted tasks are also similar (Table XI). Furthermore, the knees are bent to a similar degree in both conditions.

TABLE XI: Comparison of compression and shearing forces (N) during load lowering.

Joint	Force (N)	Restricted lifting	Unrestricted lifting
L_5/S_1	Compression	2723	2976
	Shearing	442	432

As seen in Table XI, compression forces during load lowering were highest during unrestricted lifting (2976N). When calculated as a percentage of the recommended 3400N limit, it is evident that while performing in this condition subjects are performing at 88% of the recommended limit. This lifting condition is expected to cause irreversible damage to the discs when they are exposed to tasks such as these for extended periods. Again, the unexpectedly higher compression forces in unrestricted load lowering can be explained by the technique the individual employed. It would be expected that the technique would be similar as the ceiling restriction should have no impact when placing the load and it was the same subject. However, it is evident in Figure 8(B) that the load is located slightly further from the subject's centre of mass (COM) compared to Figure 8(A), which would then increase the compression forces. Although compression forces were greater during unrestricted lifting, shearing forces were highest during restricted lifting (442N) yet the difference between shearing forces in the restricted and unrestricted lifting was only 10N. This can be attributed to the similar postures adopted as load placement is independent of ceiling height.

General Discussion

Comparisons of the ‘whole‘ lifting action which encompasses lift initiation, load lifting and load placement, shows that it is the unrestricted task that places the human operator at the most risk as this task, on average, has the highest compression and shearing forces. However, in both the lift initiation and load lifting portions of the tasks, the compression and shearing forces did not show the expected patterns. For example, compression forces were greatest during lift initiation in the restricted task. It is therefore hypothesised that it is the location of the load from the COM and the placement of the barrier in front of the load, and not the lack or presence of a reduction in ceiling height, which alters the forces in the spinal column due to changes in the lifting action at the outset of the lifting. Splittstoesser **et al**. (2007) state that the greatest degree of spinal loading occurs during the lift initiation portion of the task regardless of whether the ceiling height is increased. Furthermore, Budihardjo and Derrick (2004) report that the placement of a barrier in front of the load significantly increases peak compression forces.

In conclusion, the postural responses when using crude analyses are impacted by so many extraneous factors and hence, the findings are merely a description of what happened with one subject in two different conditions. It is evident that factors intrinsic to both the individual and the task need to seriously considered as even slight deviations in technique can have a major effect on the data obtained.

COMPARISON OF NEAR AND FAR CONDITIONS

As with the ceiling restriction analysis, the impact of reach on postural demands was also assessed using only one digital image and one subject. This subject is the same for all these analyses but different from the subject used in the previous section. Furthermore, the orientation of the mannequin on the image was positioned so that the alignment of the shoulder and hips were correct to enable accurate predictions of forces within the spinal column. From crude analysis it was evident that during the lift initiation portion of the task the compression and shearing forces within the spine were similar for both the reach distances, therefore only the impact of lowering and placing the load was explored.

Load Lowering

As is evident in Figure 9, the environmental constraint is strongly associated with the orientation of the subject's body. In both the near (A) and far (B) tasks the subject was forced to adopt a hunched posture although this is more pronounced in the near condition. The considerably greater forward trunk flexion, to avoid the environmental constraint and ensure tighter control of the load placement, in the near condition is associated with higher shearing forces (Table XII) thereby increasing the degree of strain. The neck posture is also seen to change according to the environmental constraints. In the near condition 9(A), the chin is 'tucked in' to almost lie on the chest resulting in greater neck flexion whereas in the far condition, the chin is stretched out in order to ensure that good visibility is maintained for accurate load placement. In both conditions, the subject has split the position of the feet to increase the base of support thereby increasing the degree of stability. Furthermore, the feet were placed close to the barrier further increasing the degree of movement control over the load.

FIGURE 9: Lifting postures recorded during load lifting in the (A) the near and (B) the far conditions.

TABLE XII: Forces (N) occurring within L_5/S_1 during near and far load lowering.

Joint	Force (N)	Near Placement	Far Placement
L_5/S_1	Compression	2028	2375
	Shearing	373	352

In the L_5/S_1 joint, compression forces were higher during the far load lowering (2375N) compared to near lowering (2028N). The higher compression forces with far load placement by the fact that the load was placed much further from the subject's COM. However, when investigating the differences in shearing forces, the near lowering task (373N) resulted in marginally higher forces when compared to the far lowering condition (352N). On examination of the images (Figure 9), the subject's upper body in the near (A) condition is considerably more upright in order to allow tighter control of the load placement, whereas when placing the load further away, the subject is more flexed in the upper body while adopting a semi-squat posture in the lower body thereby increasing the compression forces (Table XII).

Load Placement

Schipplein **et al**. (1995) and Gallagher (2005) state that the posture adopted during task completion alters according to task demands. The same trend was evident in this investigation (see Figure 10). During the near placement task, the subject ensured that both feet remained on the ground to ensure adequate balance. However, when placing the load far from the barrier, the body's centre of mass was displaced posteriorly by raising the back leg in order to counterbalance the effect of torques generated by the upper body and the load, which is located a substantial distance from the base of support (Figure 10). The posture adopted in the far placement task does however expose the human operator to torsional forces and places the individual at an increased risk of falling during task performance.

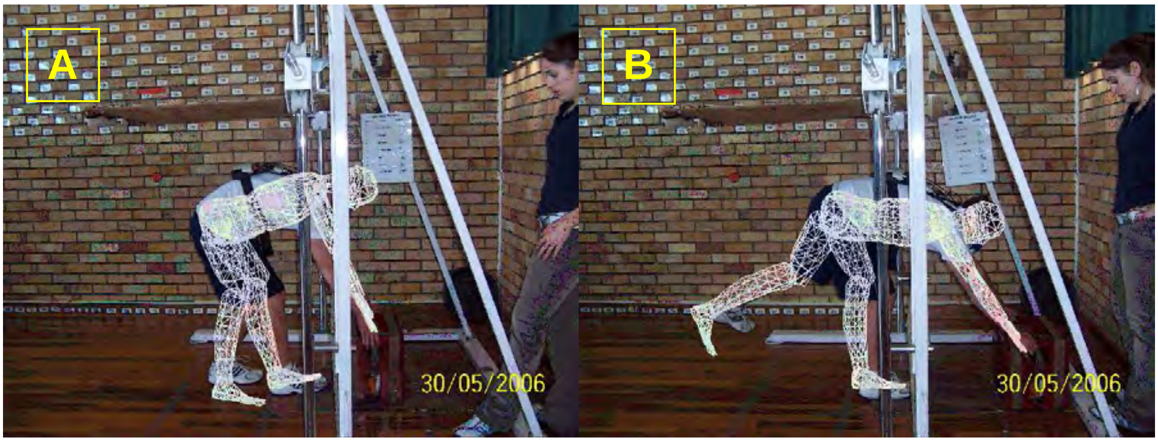


FIGURE 10: Load placement postures during (A) the near and (B) the far load placement.

In general, during load placement (Table XIII), the compression forces in both the near (3466N) and far (4935N) placement tasks were greater than the NIOSH (1981) limit of 3400N, placing the human operator at risk of developing musculoskeletal disorders. More specifically, the compression forces in the far placement task were more than 1000N greater than those in the near placement task. These differences can be attributed to the forces generated by both the load and HAT, which in turn increase the compression of the joints of the spinal column. Furthermore, the far placement task requires a substantially higher degree of muscular control to place the load accurately at further distances thereby increasing the compression forces in the spine. Shearing forces were similar in the near (435N) and far (420N) load placement (Table XIII).

TABLE XIII: Load placement forces (N) in the near and far load placement tasks.

Joint	**Force (N)**	**Near Placement**	**Far Placement**
L_5/S_1	Compression	3466	4935
	Shearing	435	420

Where: Highlighted red area refers to compression forces over the NIOSH (1981) limit of 3400N.

General Discussion

Although some of the responses recorded during this investigation are above the recommended limit, the tested population were inexperienced in manual lifting tasks and therefore may not have developed the neural pathways to reduce the strain and alter the postures adopted during load lifting and placement. It is however evident that when investigating tasks which require near and far load placement that compression forces are greater for far placement tasks whereas shearing forces are similar in both near and far placement tasks.

PHYSIOLOGICAL RESPONSES

Physiological responses provide an indication of whole-body exertion and in this study the main physical variables of interest were heart rate (HR), breathing frequency (F_B), tidal volume (V_T), minute ventilation (V_E), oxygen consumption (VO_2), respiratory quotient (RQ) and energy expenditure (EE). For all the physiological responses, conditions are referred to as URN (no ceiling restriction where the load is placed close to the barrier), RN (lowered ceiling height with a load placement close to the barrier), URF (no ceiling restriction with the load placed far from the barrier) and RF (reduced ceiling height where the load is placed far from the barrier). The responses reported on are those recorded during the third and last minute of task performance in addition to the mean responses recorded during the last four minutes of the task.

HEART RATE

As seen in Table XIV, the trend was for HR responses to increase as the lifting conditions became more hindering. HR responses, analysed using a student's t-test, increased significantly ($p < 0.05$) from 105bt.min^{-1} (minute 3) to 108bt.min^{-1} (minute 6) in the URN condition with comparable statistically significant differences evident in the other conditions. This suggests that a physiological 'steady-state' had not been reached and that the degree of cardiac strain was still increasing. Although, a 'steady-state' was not evident, the URN condition was an 'ideal' lifting task with regards to load (12kg) and lifting frequency which was 6lifts.min^{-1} (ILO, 1962; NIOSH, 1981; Mital **et al**., 1997). However, this task is only optimal if there are no obstacles or restrictions so it could be possible that the placement of a barrier over which the load was transferred placed substantially higher demands on the operator thereby affecting their ability to reach a 'steady-state'. However, because oxygen consumption (VO_2) responses displayed a 'steady-state', a more plausible explanation is that even though the laboratory procedures were tightly controlled, factors such as the subject's psychological status or whether they had ingested medication or eaten food before the testing session could have caused increases in HR which are not necessarily linked to the demands associated with the task.

A two-way ANOVA and Tukey post-hoc test demonstrated that between condition differences were also apparent. Mean heart rate responses ranged from 106bt.min^{-1} to 116bt.min^{-1} (Table XIV) depending on the degree of environmental obstruction. Subjects were working at 53.41%HR_{max}, 55.43%HR_{max} and 56.94%HR_{max} in the URN, RN and URF conditions respectively. The RF condition placed the highest demands on the subjects, with individuals working at 58.45%HR_{max} during that condition. A statistically significant 10bt.min^{-1} difference ($p < 0.05$) between lifting tasks was found between the least (URN) and most (RF) confined tasks. There was however no difference between URN, RN and URF and between the more taxing tasks, RN, URF and RF.

TABLE XIV: Mean (standard deviation) heart rate (bt.min^{-1}) responses during the different lifting conditions.

	Lifting Condition			
	URN	**RN**	**URF**	**RF**
Minute 3 HR (bt.min^{-1})	105 (± 13.49) 12.85%	107 (± 13.61) 12.72%	112 (± 13.83) 12.35%	113 (± 12.44) 11.01%
Minute 6 HR (bt.min^{-1})	108 (± 13.68)* 12.66%	111 (± 14.35)* 12.93%	116 (± 14.89)* 12.84%	118 (± 13.77)* 11.67%
Mean HR (bt.min^{-1})	106 (± 13.48) 12.72%	110 (± 14.10) 12.82%	113 (± 14.34) 12.69%	116 (± 13.14) 11.33%

**

Where: *% refers to co-efficient of variation; HR refers to heart rate; 'Mean' HR refers to the mean of HR responses recorded from minute three to minute six; * refers to a significant difference between heart rate responses in the third and sixth minute within the lifting condition; ** refers to a statistically significant difference between conditions.*

When utilising international guidelines to differentiate between confined and unrestricted industrial tasks, the statistically significant differences in strain experienced by the human operator is frequently indistinguishable. For example, according to the criteria of the American Industrial Hygiene Association (1971), all tasks are considered to place equal ('moderate') demands on the human operator despite the statistically significant difference obtained. Likewise, Åstrand and Rodahl (1977) classify all conditions tested as 'moderate' to 'heavy' and again all tasks are categorised as taxing the individual to a similar degree. In contrast, other criteria (Ayoub and Mital,

1989) grade the two restricted and unrestricted tasks differently. For example the URN (106bt.min^{-1}) task is considered acceptable for an 8h working day yet the URF (113bt.min^{-1}) task is not regarded as satisfactory even though both tasks have the same degree of ceiling constraint. In this instance, the reach distance impacted the recommendations. A similar trend is evident when comparing the conditions where the depth of reach changes. The lifting tasks where the reach demands were 400mm are considered to be ‘moderate’ (American Industrial Hygiene Association, 1971; Åstrand and Rodahl, 1977) yet when the reach parameter is increased to 800mm, some criteria (American Industrial Hygiene Association, 1971) consider these activities to be ‘moderate’, while others regard the tasks as ‘heavy’ (Åstrand and Rodahl, 1977). Ayoub and Mital (1989) categorise the tasks where the load is placed close to the barrier as acceptable for extended work whereas when the load is placed at 800mm, these authors suggest that these tasks should not be performed for extended periods. It is therefore evident that in the case of reach, the elevation of the ceiling does not have a distinguishable effect when only utilising the international guidelines.

In comparing the overall difference between the restricted and unrestricted conditions, a statistically significant ($p < 0.05$) increase of 3.11% in mean heart rate responses was evident when subjects were restricted. This is similar to the findings of Gallagher and Hamrick (1992) who found a 4% difference. The fact that these authors compared kneeling and stooped lifting could account for the 1% higher difference between their two conditions.

The effect of increasing reach from 400mm to 800mm placed a significantly greater demand ($p < 0.05$) on the human operator, resulting in a 5.68% increase in mean heart rate. These findings are less than those reported by Sengupta and Das (2004), who identified that HR increased by between 6% and 14% depending on the extent of the reach demands. Although the findings in the Sengupta and Das (2004) investigation are higher than this study, their subjects performed a lateral lift instead of a horizontal lift at waist height. Garg and Saxena (1982) also found no statistically significant difference between HR responses over different reach distances. A possible explanation for the lack of statistically significant difference in Garg and Saxena's (1982) subjects could be that the task required the lifts to be performed with one hand and the load ranged from 1.1kg to 5.7kg, which may not tax the individuals to the same degree. The subjects in another study (Habes **et al**. 1985) also did not show a statistically significant change in cardiovascular responses when the placement distance was increased. The significantly higher responses in the far (800mm) condition in this investigation can be attributed to the extensive changes in body posture when placing the load far from its origin. Subjects tended to lift their back leg (see Figure 12) to counterbalance the effects of the weight of the head, arms and trunk which were located on the other side of the barrier when lowering and placing the load. This caused the blood to move with the effects of gravity from the lower extremities towards the heart thereby increasing venous return. The heart therefore responded by increasing its output to restore homeostasis. The combination of reach distance and ceiling height did not however have a statistically significant effect on HR responses.

BREATHING RESPONSES

Due to the lifting task requiring the predominant use of the muscles located in the arms, the movement of the rib cage was restricted which in turn affected the breathing responses (Table XV). Breathing frequency (F_B) increased significantly ($p < 0.05$) from the third to the sixth minute in two of the lifting conditions (RN and RF). A 'steady-state' was therefore only reached in the non-restrictive conditions (URN and URF). In contrast to the breathing frequency responses, tidal volume (V_T) did not reach a 'steady-state' when the load was placed close to the barrier and the ceiling was lowered (RN). However, similarly to the breathing frequency responses V_T did not reach a 'steady-state' in the most confined condition (RF). It was unexpected that a state of equilibrium with regards to V_T was not reached in what could arguably be the most ideal condition (URN). The general trend (refer to Table XV) in the URN condition was therefore for F_B to remain statistically stable while V_T increased significantly over time. In the RN condition, however, V_T remained statistically stable with statistically significant increases evident in F_B. With regards to the RF condition, statistically significant increases in both F_B and V_T were seen whereas in the URF condition, both F_B and V_T remained statistically stable. With respect to minute ventilation (V_E), subjects utilised a greater proportion of air in all conditions to perform gaseous exchange in the sixth minute when compared to the third minute of task performance. It is therefore evident that the demands of the task were still increasing and a homeostatic state had not been reached with regards to V_E.

TABLE XV: The effect of environmental restriction on mean (standard deviation) breathing responses.

	Lifting Condition			
	URN	**RN**	**URF**	**RF**
Mean F_B (br.min^{-1})	18.91 (± 3.77) 19.94%	19.26 (± 3.92)* 20.35%	19.49 (± 3.87) 19.86%	19.67 (± 3.53)* 17.95%
Mean V_T (L)	1.56 (± 0.34)* 21.79%	1.70 (± 0.47) 27.65%	1.72 (± 0.36) 20.93%	1.86 (± 0.42)* 22.58%
Mean V_E (L.min^{-1})	28.15 (± 3.69)* 13.11%	31.16 (± 5.42)* 17.39%	32.17 (± 4.29)* 13.34%	35.42 (± 6.34)* 17.90%

**

Where: *% refers to the co-efficient of variation; F_B refers to breathing frequency; V_T refers to tidal volume; V_E refers to minute ventilation; 'Mean' refers to the mean of responses recorded from minute 3 to minute 6; * refers to a statistically significant difference between minute three and six responses within the condition; ** refers to a statistically significant difference between conditions.*

Seen in Table XV, mean F_B, V_T and V_E were lowest during the least constrained condition (18.91br.min^{-1}, 1.56L and 28.15L.min^{-1} respectively) and increased to 19.67br.min^{-1}, 1.86L and 35.42L.min^{-1} respectively in the most confined condition (RF). During the RF condition, V_T was significantly higher, by 0.3L, than when performing in the URN situation. There was however no difference found between the URN, RN and URF conditions (Table XV). V_E was significantly ($p < 0.05$) lower in the most ideal condition (URN) compared to the condition with no ceiling restriction but with the load placed far away (URF) and was significantly lower than the most hindering task (RF). Furthermore, significantly higher minute ventilation responses occurred in the RF task when compared to the RN condition. According to the reference values of McArdle and colleagues (2001), the subject's breathing responses (F_B, V_T, V_E) in all conditions are similar to those seen when individuals progress from a state of rest to moderate physical activity.

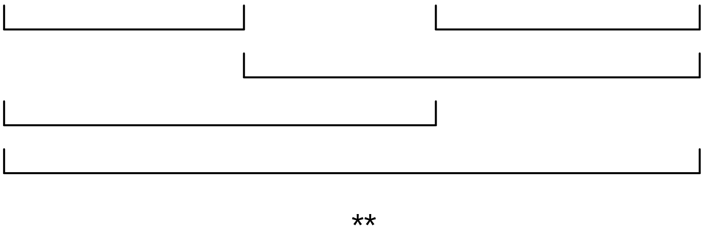
There was a statistically significant increase ($p < 0.05$) of 1.37% in mean breathing frequency responses when comparing lifting with no ceiling restriction and with a ceiling restriction. There was also a statistically significant increase ($p < 0.05$) in these responses with increasing reach distance (2.53%). With respect to tidal volume, a reduction in ceiling height resulted in a mean statistically significant increase of 7.89% while placement distance resulted in a statistically significant increase of 8.95%. Mean minute ventilation responses were also significantly affected ($p < 0.05$) by reducing the ceiling height (9.42%) and increasing the reach demands (12.27%). It is therefore evident that tidal volume had a greater effect on minute ventilation than breathing frequency.

OXYGEN CONSUMPTION

In all conditions, oxygen consumption (VO_2) increased in a similar trend from minute 3 to minute 6 (Table XVI). The smallest volume of oxygen consumed (15.06ml.kg^{-1}.min^{-1}) occurred in minute three while subjects lifted the load in the URN condition with the highest oxygen consumption (19.43ml.kg^{-1}.min^{-1}) occurring in the sixth minute of lifting in the most restrictive (RF) condition (Table XVI). In all lifting conditions, there was no statistically significant difference ($p > 0.05$) between the responses recorded during the third and sixth minute indicating that subjects had reached a physiological ‘steady-state’ with respect to oxygen uptake.

TABLE XVI: The mean (standard deviation) oxygen consumption (VO$_2$) responses recorded in the test sample during the different lifting conditions.

	Lifting Condition			
	URN	**RN**	**URF**	**RF**
Minute 3 VO$_2$ (ml.kg^{-1}.min^{-1})	15.06 (± 1.70) 11.29%	16.67 (± 2.51) 15.06%	17.82 (± 2.02) 11.34%	18.93 (± 2.98) 15.74%
Minute 6 VO$_2$ (ml.kg^{-1}.min^{-1})	15.15 (± 1.77) 11.68%	16.54 (± 2.30) 13.91%	17.75 (± 2.16) 12.17%	19.43 (± 2.81) 14.46%
Mean VO$_2$ (ml.kg^{-1}.min^{-1})	15.01 (± 1.63) 10.86%	16.55 (± 2.45) 14.80%	17.78 (± 2.06) 11.59%	19.28 (± 2.79) 14.47%



Where: *% refers to co-efficient of variation; VO$_2$ refers to oxygen consumption; ‘Mean’ refers to the mean of responses recorded from minute 3 to minute 6; ** refers to a statistically significant difference between conditions.*

Mean oxygen consumption ranged from 15.01ml.kg^{-1}.min^{-1} (URN) to 19.28ml.kg^{-1}.min^{-1} (RF) depending on the degree of environmental restriction. Mean oxygen consumption was significantly greater in the RN (16.55ml.kg^{-1}.min^{-1}) condition compared to the most ‘ideal’ condition (URN). The same trend was evident between URF (17.78ml.kg^{-1}.min^{-1}) and RF (19.28ml.kg^{-1}.min^{-1}) where significantly greater ($p < 0.05$) mean oxygen consumption occurred in the more restrictive task (RF). A statistically significant difference was also evident between the most confined condition (RF) and the lifting task where the ceiling was lowered but load placement was close to the barrier (RN). Finally, the two most constrained conditions, URF and RF, resulted in significantly greater mean oxygen consumption responses than the URN condition (15.01ml.kg^{-1}.min^{-1}).

According to the guidelines of McArdle **et al**. (2001), the least restrictive lifting task, URN, is classified as a ‘light’ workload with a mean VO_2 of 15.01ml.kg^{-1}.min^{-1}. The more constrained tasks, RN (16.55ml.kg^{-1}.min^{-1}), URF (17.78ml.kg^{-1}.min^{-1}) and RF (19.28ml.kg^{-1}.min^{-1}), are however considered to be ‘moderately’ taxing. It is therefore apparent that the present physiological guidelines are not able to distinguish between statistically significant changes in task parameters which in turn affects the load experienced by the human operator in constrained conditions. However, oxygen consumption can also be represented as a percentage of maximal oxygen consumption. According to the cardiovascular fitness criteria (McArdle **et al**., 2001) subjects were working at 38.5%VO_{2max}, 42.5%VO_{2max} and 45.6%VO_{2max} in the URN, RN and URF conditions respectively (refer to Table VI). The RF condition placed the highest demands on the human operator with subjects performing at 49.5%VO_{2max} during the task. Suggested guidelines proposed by Wu and Wang (2002) argue that individuals may work at a level of 43%VO_{2max} when the shift is only 4hours long however when the work duration is increased to eight hours, workers should only be performing at 34%VO_{2max}. It is therefore evident that subjects, even when lifting in the least restrictive condition (URN), are performing at a level which is greater than the recommended level placing individuals at risk of fatigue and possible injury.

The overall effect of ceiling elevation on mean VO_2 responses was statistically significant with subjects consuming a greater (8.55% more) volume of oxygen in conditions where the roof height is reduced. The effect of increasing reach distance from 400mm to 800mm was also statistically significant with mean VO_2 responses increasing by 14.87%. Both of these findings are plausible as the body requires a greater amount of oxygen, and hence energy, when performing more strenuous tasks.

Relationship Between Heart Rate and Oxygen Consumption

The heart rate and oxygen consumption responses recorded during the lifting conditions were utilised to develop group regression equations between these two variables. The reason being that the relationship between these two variables can differ substantially as the task demands are manipulated; this can be seen in Figure 12. Although various authors have suggested that individual regressions between heart rate and oxygen consumption responses would improve the accuracy of predicting VO_2 from HR responses, a group regression was established for each lifting condition which is considered useful when individual testing is not feasible when testing large samples (Scott and Christie, 2004).

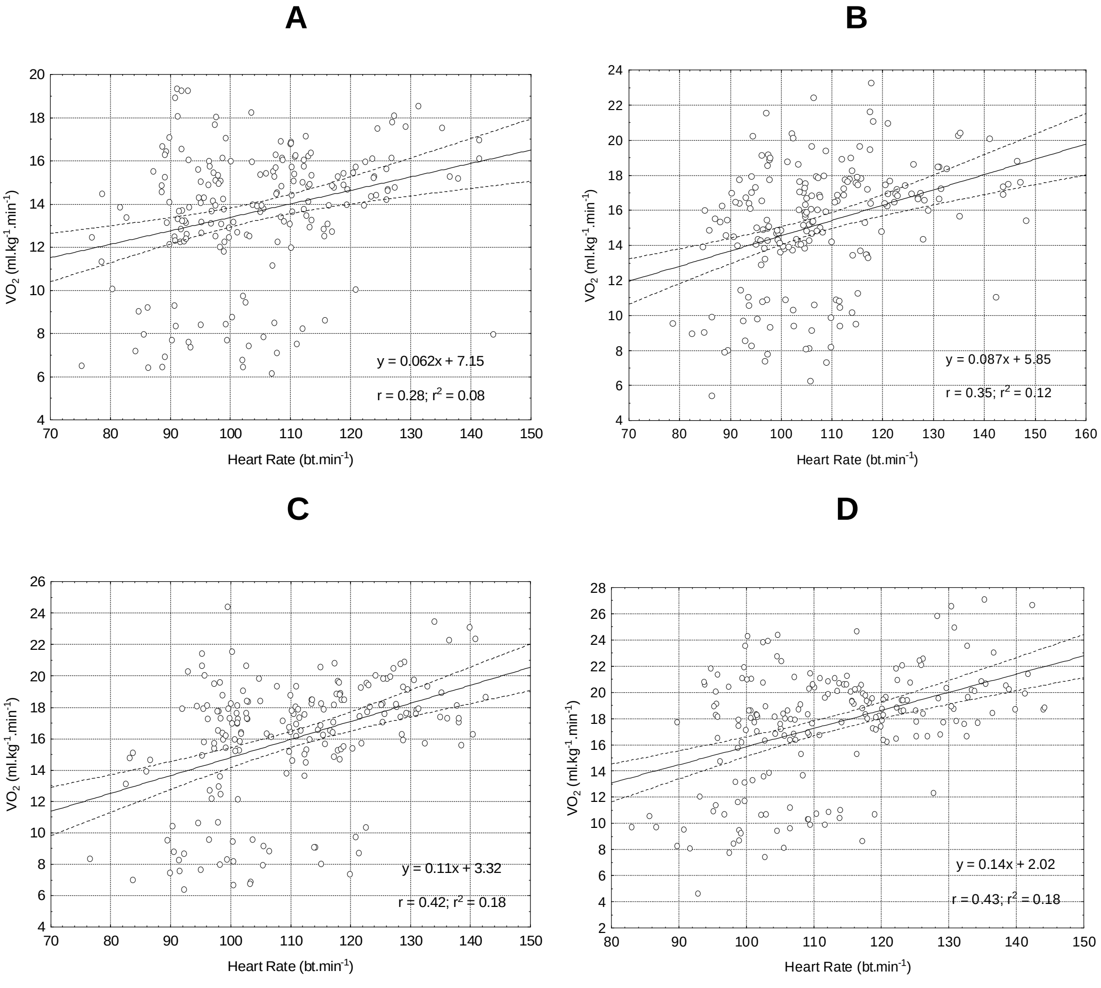


FIGURE 11: Relationship between heart rate and oxygen consumption

(A: unrestricted lifting with a close load placement; B: a lowered ceiling with the load placed close; C: unrestricted lifting with the load placed far; D: lowered ceiling with the load placed far).

The group regression equations varied substantially depending on the combination of ceiling height and reach demands (Figure 12). The lowest predictive efficiency (r^2) was 0.08 ($y = 0.062^* x + 7.15$) in the least confined condition (URN) where only 8% of the variance in VO_2 can be explained by the variance in HR. The highest r^2 was only 0.18 in the two conditions where the reach demands were 800mm (URF and RF). However, even in these two conditions only 18% of the variance in VO_2 can be explained by the variance in HR. This was an unexpected finding especially for the more taxing conditions as these types of tasks have been shown to elicit tighter relationships than less intense tasks (Wolfe, 2004; Christie, 2006).

RESPIRATORY QUOTIENT

Respiratory quotient (RQ) in the most ‘ideal’ condition (URN) increased significantly ($p < 0.05$) from 0.86 (54.1% carbohydrates; 45.9% lipids) in the third minute of task performance to 0.93 (77.4% carbohydrates; 22.6% lipids) in the sixth minute (Table XVII). Similar statistically significant increases in RQ were also evident in all other conditions. The increase in the percentage of carbohydrates oxidised indicates that the intensity of the task was increasing, which supports the work of Brooks and Mercier (1994), who suggest that substrate utilisation ‘crosses over’ from a predominance of lipids to a greater percentage of carbohydrates as the intensity of the task increases. Subjects had therefore not reached a ‘steady-state’ with regards to RQ responses.

Between condition differences were not apparent between any of the tasks indicating that the mean RQ, and hence substrate utilisation, was similar in all conditions. The effect of reach distance was however statistically significant. In the near placement (400mm) tasks regardless of ceiling height (URN and RN) the mean RQ data indicates that subjects oxidised 67.5% carbohydrates and 32.5% lipids. During the tasks where the reach distance was 800mm (URF and RF) subjects utilised a significantly greater proportion of carbohydrates (70.8%) and therefore a significantly lower proportion of lipids (29.2%).

TABLE XVII: Mean (standard deviation) respiratory quotient responses recorded during the lifting tasks.

	Lifting Condition			
	URN	**RN**	**URF**	**RF**
Minute 3 RQ	0.86 (± 0.07) 8.14%	0.85 (± 0.07) 8.24%	0.86 (± 0.06) 6.98%	0.86 (± 0.06) 6.98%
Minute 6 RQ	0.93 (± 0.05)* 5.38%	0.94 (± 0.04)* 4.26%	0.95 (± 0.05)* 5.26%	0.96 (± 0.04)* 4.17%
Mean RQ	0.90 (± 0.06) 6.67%	0.90 (± 0.05) 5.56%	0.91 (± 0.06) 6.59%	0.91 (± 0.05) 5.50%

*Where: % refers to co-efficient of variation; RQ refers to respiratory quotient; 'Mean' refers to the mean of the data collected from minute 3 to minute 6; * refers to a statistically significant difference within conditions between the third and sixth minute of responses.*

ENERGY EXPENDITURE

As is evident in Table XVIII, an increase in the degree of restriction is associated with a concomitant increase in the activity based energy expenditure. Energy expenditure only showed a statistically significant increase from the third to the sixth minute of lifting in the URN (from 24.06kJ.min^{-1} to 24.61kJ.min^{-1}) and RF (from 30.56kJ.min^{-1} to 32.20kJ.min^{-1}) conditions. This effectively suggests that a physiological 'steady-state' was only reached in the RN and URF conditions yet the strain experienced by the human operator was still increasing in the URN and RF conditions.

Mean energy cost ranged from 24.20kJ.min^{-1} (URN) to 31.56kJ.min^{-1} (RF) depending on the degree of constraint (Table XVIII). Mean energy expenditure was significantly higher ($p < 0.05$) in the RN condition (27.04kJ.min^{-1}) compared to the URN condition. Furthermore, significantly greater energy utilisation occurred in the URF task (28.75kJ.min^{-1}) compared to the URN condition (24.20kJ.min^{-1}). EE was also found to increase significantly from 24.20kJ.min^{-1} in the most ‘ideal’ condition (URN) to 31.56ml.kg^{-1}.min^{-1} in the least ‘ideal’ task (RF). Additionally, a statistically significant increase in energy expenditure occurred between conditions where the ceiling was lowered but the reach demands (RN and RF) were different. The elevated energy expenditure values associated with progressively more restrictive environments concur with past research (Sanders and McCormick, 1992; Gallagher **et al**., 1994; Kumar **et al**., 2000; Gallagher, 2005).

TABLE XVIII: Mean energy cost (standard deviation) associated with lifting in different simulated environments.

	Lifting condition			
	URN	**RN**	**URF**	**RF**
Minute 3 EE (kJ.min^{-1})	24.06 (± 3.06) 12.72%	26.83 (± 4.06) 15.13%	28.46 (± 3.46) 12.16%	30.56 (± 5.16) 16.88%
Minute 6 EE (kJ.min^{-1})	24.61 (±3.17)* 12.88%	27.31 (± 4.60) 16.84%	28.99 (± 3.49) 12.04%	32.20 (± 5.22)* 16.21
Mean EE (kJ.min^{-1})	24.20 (± 2.94) 12.15%	27.04 (± 4.44) 16.42%	28.75 (± 3.56) 12.38%	31.56 (± 5.03) 15.94%

**

*Where: % refers to co-efficient of variation; EE refers to energy expenditure; ‘Mean’ refers to the mean of the responses from minute 3 to minute 6; * refers to a statistically significant difference between responses in minute three and six; ** refers to a statistically significant difference between conditions.*

According to the categorisation of tasks by the American Industrial Hygiene Association (1971) and McArdle **et al**. (2001), the URN (5.78kcal.min^{-1}), RN (6.46kcal.min^{-1}) and URF (6.87kcal.min^{-1}) tasks are considered to place ‘moderate’ demands on the operator whereas the RF (7.54kcal.min^{-1}) condition is classified as a ‘heavy’ workload. Again, although there was a statistically significant difference between many of the conditions, the ergonomic guidelines still categorise most of these conditions as placing similar demands on individual. The proposed limits of 5.0kcal.min^{-1} (20.93kJ.min^{-1}) and 4.0kcal.min^{-1} (16.74kJ.min^{-1}) suggested by Dempsey (1998) and Mital (1999) respectively, suggest that all these conditions are unacceptable for extended work.

Energy expenditure increased significantly ($p < 0.05$), and by 9.7% in instances where the ceiling height was reduced. These findings support those of Morrissey **et al**. (1985) and Kumar **et al**. (2000) who reported that the greater the deviation from an upright bipedal stance, the higher the energy cost to the individual. Likewise, independent of ceiling height, there was a mean statistically significant increase of 15.08% in energy expenditure when the reach distance increased from 400mm to 800mm, which supports the research of Habes **et al**. (1985).

PERCEPTUAL RESPONSES

In an attempt to gain a holistic and tangible measure of the subject’s perception of physical demands of the lifting tasks, ‘central’ and ‘local’ Ratings of Perceived Exertion responses together with Body Discomfort responses were recorded.

‘CENTRAL’ RATING OF PERCEIVED EXERTION

The degree to which the lifting tasks were perceived to tax the subject’s cardiorespiratory system changed according to the degree of environmental restriction (Table XIX). In the URN task, student’s t-tests revealed that ‘central’ Ratings of Perceived Exertion (CRPE) increased significantly from 9 (‘very light’ effort) in the third minute of lifting to 10 (‘very light’ to ‘fairly light’ effort) in the sixth minute of lifting. Comparable statistically significant increases ($p < 0.05$) were also seen in all other conditions. Subjects were therefore able to perceive that a physiological ‘steady-state’ had not been reached, which is reflected in the both HR (see Table XIV) and minute ventilation (see Table XV) responses. This finding was expected, as the paradigm on which CRPE was devised was that for every 10bt.min^{-1} increase in HR responses, CRPE responses should increase by one unit. Furthermore, even though oxygen consumption responses had reached a ‘steady-state’ (see Table XVI) this was not perceived by the subjects as CRPE was only devised to be a reflection of HR responses.

TABLE XIX: Mean (standard deviation) ‘Central’ Rating of Perceived Exertion (CRPE) responses during the lifting tasks.

	Lifting Condition			
	URN	**RN**	**URF**	**RF**
Minute 3 CRPE	9 (± 1.76) 19.56%	10 (± 1.95) 19.50%	10 (± 1.85) 18.50%	11 (± 2.01) 18.27%
Minute 6 CRPE	10 (± 1.94)* 19.40%	10 (± 2.03)* 20.30%	11 (± 2.03)* 18.45%	12 (± 2.14)* 17.83%
Mean CRPE	10 (± 1.92) 19.20%	10 (± 2.03) 20.30%	11 (± 2.01) 18.27%	11 (± 2.15) 19.55%

**

Where: *% refers to co-efficient of variation; CRPE refers to ‘central’ Rating of Perceived Exertion; ‘Mean’ refers to the mean of the responses collected in the minute 3 and minute 6; * refers to a statistically significant difference within conditions between the third and sixth minute of responses; ** refers to a statistically significant difference between conditions.*

Statistical analysis through a two-way ANOVA and Tukey post-hoc tests revealed that subjects perceived that the least confined tasks, URN and RN, placed equal strain (10; ‘very light’ exertion to ‘fairly light’ exertion) on the cardiorespiratory system (Table XIX). The same trend was evident in the more confined conditions with the URF and RF lifting tasks placing similar strain (11; ‘fairly light’ effort) on the subjects. A significantly greater degree of strain ($p < 0.05$) was however perceived to occur in the least ‘ideal’ (RF) condition when compared to the URN and RN lifting tasks, indicating that the subjects were able to perceive the effects of the environmental constraints and that the tasks were becoming progressively more taxing on the cardiorespiratory system.

With regards to the effects of ceiling height and reach demands, only the effect of reach was found to have a statistically significant effect ($p < 0.05$) on the manner in which the subjects perceived the task. CRPE was therefore 9.09% greater in the tasks where the load was placed 800mm away from the barrier compared to when subjects only moved it 400mm, which supports the findings of Habes **et al**. (1985). The lack of difference between the tasks where the ceiling is lowered and where the elevation of the ceiling is ‘normal’ is contradictory to the findings of Rückert **et al**. (1992) and Kumar **et al**. (1993). Noteworthy in this investigation, however, is that with all the physiological responses, reach had a greater impact than ceiling restriction which was then perceived to be more stressful by the subjects. Therefore, the degree of change in the physiological responses with reductions in ceiling height may not be sufficient to be detected by the subjects and hence their perceptual ratings remained the same.

‘LOCAL’ RATING OF PERCEIVED EXERTION

Subjects perceived the more hindering tasks to place greater strain on the musculoskeletal system, more specifically the upper extremities and the back (Table XXI). ‘Local’ Rating of Perceived Exertion (LRPE) during the third minute of lifting in the URN condition were 9 (‘very light’ effort) and then increased significantly to 10 (‘very light’ to ‘fairly light’ effort) in the sixth minute of lifting. Similar statistically significant increases ($p < 0.05$) were seen in all other conditions between the third and sixth minute of lifting. Furthermore, the trends evident in LRPE were comparable to those seen in CRPE (see Table XIX).

TABLE XX: Mean (standard deviation) ‘Local’ Rating of Perceived Exertion responses during the lifting tasks.

	Lifting Condition			
	URN	**RN**	**URF**	**RF**
Minute 3 LRPE	9 (± 1.62) 18.00%	9 (± 1.87) 20.78%	10 (± 1.85) 18.50%	10 (± 1.67) 16.70%
Minute 6 LRPE	10 (± 2.02)* 20.20%	11 (± 2.46)* 22.36%	11 (± 2.03)* 18.45%	11 (± 2.13)* 19.36%
Mean LRPE	9 (± 1.92) 21.33%	10 (± 2.29) 22.90%	10 (± 2.00) 20.00%	11 (± 2.34) 21.27%

**

Where: *% refers to co-efficient of variation; LRPE refers to ‘Local’ Rating of Perceived Exertion; ‘Mean’ refers to the mean of the responses from the third and sixth minute * refers to a statistically significant difference within conditions between the third and sixth minute of responses; ** refers to a statistically significant difference between conditions.*

Mean ‘local’ Rating of Perceived Exertion (LRPE) responses were lowest in the least confined condition (9; ‘very light’ effort) and highest in the most severely constrained lifting task (11; ‘fairly light’ effort) where the ceiling was lowered and the load placed far from the barrier. Significantly lower ($p < 0.05$) mean LRPE responses were seen in the URN condition when compared to responses in the most restrictive condition (RF). This finding is supported by the research of Habes and colleagues (1985) and the number of musculoskeletal complaints from the Body Discomfort Map (see Table XXI) with the most restrictive condition (RF) resulting in a greater number of discomfort reports than the URN condition. All other lifting conditions were perceived as placing equivalent strain on the musculoskeletal system.

Both the effect of ceiling height and reach demands were seen to significantly ($p < 0.05$) affect the manner in which subjects perceived that the task taxed the musculoskeletal system. Working under a lowered ceiling height resulted in subjects reporting that the musculoskeletal strain (LRPE) was 10.0% greater than a ‘normal’ ceiling height with similar increases (9.55%) occurring when subjects placed the load further from the barrier. This finding was opposite to the relationship between the physiological and CRPE responses where reach caused a greater increase in CRPE responses.

BODY DISCOMFORT RESPONSES

Body discomfort is an important factor which enables one to assess the manner in which subjects perceive the demands imposed upon them (Corlett and Bishop, 1976). In this investigation, the assessment of body discomfort revealed the awkwardness of the posture and the corresponding musculoskeletal load imposed by the lifting conditions, thereby assisting in identifying possible areas of risk. Each subject was required to identify the top three areas of discomfort from the Body Discomfort map and specify the degree of discomfort experienced. As the vast majority of body discomfort reports came from the posterior regions of the body, only these are discussed.

As is evident in Table XXI, the lower back area had the highest percentage of discomfort reports in all conditions which is in agreement with the research of Habes **et al**. (1985) and Senguta and Das (2004). The highest number of reports (75%) occurred when the load was placed close to the barrier and the ceiling height was reduced (RN). This can be attributed to the hunched posture that needed to be adopted to ensure that the posterior regions of the body did not come into contact with the ceiling and to enable accurate placement of the load.

TABLE XXI: The main areas of discomfort reported during the lifting tasks.

URN		RN		URF		RF	
Region	**%**	**Region**	**%**	**Region**	**%**	**Region**	**%**
Lower back	47 (4)	Lower back	75 (4)	Lower back	41 (5)	Lower back	69 (6)
Upper back	13 (4)	Buttocks	25 (4)	Middle back	22 (5)	Buttocks	28 (5)
Middle back	9 (5)	Neck	16 (4)	Right thigh	16 (4)	Right thigh	19 (5)

Where: % refers to the percentage of subjects who reported the area of discomfort with mean discomfort ratings seen in brackets.

The greatest degree of discomfort (rating of 6) within the lower back region was however reported in the most restrictive task where the load was placed furthest from its origin (RF), which is in agreement with the findings of Habes and colleagues (1985). The higher discomfort levels in this condition can be linked to the combination of the stress imposed by the reduced height of the ceiling and the cumulative feelings of fatigue from raising the leg during load placement. Further evidence to support this claim is apparent in the high number of reports of discomfort in the gluteal region (28%) and posterior right thigh (19%). However, the number of discomfort reports in the gluteal region could also be attributed to the lowered ceiling height as 25% of subjects also reported discomfort in the RN condition. Furthermore, in the URF condition where the load was also placed far from its origin, high numbers of reports in the gluteal region are lacking. It is therefore evident that the gluteal discomfort is more plausibly associated with the reduction in ceiling height. The discomfort experienced in the right thigh within the URF (16%) and RF (19%) conditions are however linked to the strain imposed by the mass of the subject and the load when the left leg was lifted to counterbalance the torques generated during load placement. In the unrestricted conditions (URN and URF), the second highest percentage of discomfort reports occurred in the upper (URN) and middle back (URF) areas with the middle back (9%) and right thigh (16%) third highest in the URN and URF conditions respectively.

CONCLUSION

Overall postural, physiological and perceptual responses showed that the most strain occurred while subjects performed in the most restricted condition (RF). Subjects were exposed to the least amount of strain when lifting in the most ‘ideal’ condition, URN. Less obvious were the findings in the other two conditions, RN and URF, where there was no statistically significant difference between these conditions in any of the responses recorded. Overall, the reach demands appear to have a greater impact on responses than the height of the ceiling indicating that should these two factors be present in the same task, it is the reach factor that drives the responses. Interestingly, no statistically significant effect was evident when the effect of ceiling height and reach demands were evident in any of the variables.

CHAPTER V

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

INTRODUCTION

As lower back pain has been the predominant occupational injury (Marras **et al**., 1999), the focus of most ergonomic investigations has been on the biomechanical stresses occurring in the working environment (Granata and Wilson, 2001; Kingma and Dieën, 2004) with a lack of information about the physiological and perceptual strain experienced by the human operator. Furthermore, although research has focused on the implications of lowered ceiling heights and extreme reach conditions, the interaction of these effects is not well established. The objective of this study was therefore to determine the strain experienced by the human operator within constrained working conditions where the ceiling height was lowered and reach demands varied.

SUMMARY OF PROCEDURES

In an attempt to determine the implications of a lowered ceiling height and different reach demands in a real lifting task, thirty-two healthy physically active male subjects were recruited for this investigation. The subjects' stature was limited to between 1750mm and 1900mm and the subjects did not have any recent upper body or lower back injuries. Subjects were required to complete four conditions, two of which where the ceiling height was lowered to 1460mm (76 – 80% of stature) and in the other two conditions, there was no ceiling restriction. The load was then placed either 400mm or 800mm from its origin. In all four conditions, a 12kg load was lifted in a standing freestyle posture from the floor and over a barrier located at knee height (554mm). The lifting frequency was a constant 6lifts.min^{-1} and each task lasted a total duration of six minutes.

During all conditions, photographic images of the lifting postures were taken during the third and last minute of the task. These images were taken during the initiation of the lift, during load lifting and load lowering. Physiological responses (heart rate, breathing frequency, tidal volume, minute ventilation, oxygen consumption, respiratory quotient, energy expenditure) were monitored continuously throughout the duration of the task using a Polar® S410 Heart Rate monitor and an online ergospirometer, the Cosmed K4b^{2}®. At the completion of each three-minute period during all lifting sessions, subjects were required to identify the extent to which they perceived the lifting tasks to tax the cardiorespiratory ('Central') and the musculoskeletal ('Local') systems through the use of Borg's Rating of Perceived Exertion (RPE) scale. Furthermore, areas of discomfort and the intensity of the discomfort experienced were reported at the end of each task through the use of the Body Discomfort Map. As the focus of this investigation was to determine the effects of ceiling height and reach demands on the human operator, all other task factors such as lifting duration were kept constant throughout the testing sessions.

SUMMARY OF RESULTS

With respect to the postural analyses, during the lift initiation subjects experienced the greatest compression forces (3061N) in the restricted task whereas shearing forces (337N) were higher in the unrestricted lifting task. While lifting the load, both compression (2257N) and shearing (396N) forces were greatest in the unrestricted task. The compression forces were also higher in the unrestricted task (2976N) during load lowering but shearing forces (442N) were greater in the restricted task. Overall, the unrestricted task placed the human operator under the greatest strain not because of the posture adopted but because the load was held further away from the subject's centre of mass (COM). Comparisons between the load lowering portion of the task in the near and far placement lifting tasks showed that the far placement task resulted in the greatest compression forces (2375N) whereas shearing forces were highest in the near placement task (373N). Compression and shearing forces followed the same trend in the load placement portion of the tasks, with 4935N of compression stress experienced in the far task and 435N of shearing forces occurring in the near task.

Heart rate (HR) responses ranged from 105bt.min^{-1} to 113bt.min^{-1} in the third minute of lifting to between 108bt.min^{-1} and 118bt.min^{-1} in the sixth minute depending on the lifting condition. Responses were significantly higher ($p < 0.05$) during the sixth minute of lifting in all lifting conditions indicating that a physiological 'steady-state' had not been reached. Mean HR responses ranged from 106bt.min^{-1} to 116bt.min^{-1} with significantly greater responses ($p < 0.05$) occurring in the most restrictive condition (RF) when compared to the most 'ideal' task (URN). A lowered ceiling height and an increase in the depth of reach were both found to result in significantly ($p < 0.05$) higher HR responses than when there was no ceiling restriction or excessive reach demands.

Statistically significant differences in breathing frequency (F_B) responses were evident between the third and sixth minute of lifting in the two most restrictive conditions (RN and RF). The effect of a lowered ceiling height resulted in a statistically significant increase of 1.37% in mean breathing frequency with the effect of an increase in reach depth resulting in a 2.53% increase in mean F_B. Mean tidal volume (V_T) ranged from 1.56L (URN) to 1.86L (RF) depending on the degree of environmental restriction. A statistically significant difference between the responses in the third and sixth minute of lifting was only evident between the most (URN) and least (RF) 'ideal' tasks with 'steady-state' being reached in the RN and URF conditions. Mean tidal volume was significantly different between the URN and RF conditions. A decrease in ceiling height and an increase in the depth of reach were both associated with statistically significant increases ($p < 0.05$) in V_T. With respect to minute ventilation (V_E), significantly greater responses ($p < 0.05$) occurred during the sixth minute of the task when compared to the third minute of lifting in all tasks. Mean V_E was significantly lower in the least restrictive task (URN) when compared to the conditions where the reach demands were 800mm (URF and RF). A further statistically significant difference between conditions was evident between the conditions were the roof elevation was lowered (RN and RF). Both an increase in the reach demands from 400mm to 800mm and a reduction in the height of the ceiling are associated with statistically significant increases ($p < 0.05$) in minute ventilation.

Oxygen consumption (VO_2) ranged from 15.06ml.kg^{-1}.min^{-1} (minute 3) in the least restrictive condition (URN) to 19.43ml.kg^{-1}.min^{-1} (minute 6) in the most restrictive task (RF). Responses in the third minute of lifting were not significantly lower than those in minute six, indicating that a physiological ‘steady-state’ had been reached in all conditions with regards to VO_2. Mean VO_2 responses were significantly greater in the most restrictive (RF) condition (19.28ml.kg^{-1}.min^{-1}) when compared to the RN (16.55ml.kg^{-1}.min^{-1}) and URF (17.78ml.kg^{-1}.min^{-1}) conditions. Furthermore, performance in the most ‘ideal’ condition (URN) required significantly less oxygen than in all of the other conditions. Lowering the ceiling height resulted in a statistically significant increase of 8.55% in VO_2 while increasing the reach demands led to a statistically significant (14.87%) increase in VO_2. The combination of these two factors did not have a statistically significant impact on the amount of oxygen consumed.

Respiratory quotient (RQ) ranged from 0.85 (RN) to 0.96 (RF) depending on the degree of environmental restriction. In all lifting tasks, RQ responses in the third minute were significantly lower ($p < 0.05$) than those recorded in the sixth minute of lifting. Mean RQ responses were similar in all conditions. When the reach demands were increased from 400mm to 800mm, a statistically significant difference ($p < 0.05$) in RQ responses was evident; however, reducing the elevation of the ceiling did not have a statistically significant impact on RQ responses.

Energy expenditure (EE) increased from 24.06kJ.min^{-1} (minute 3) to 24.61kJ.min^{-1} (minute 6) in the least confined task (URN) with similar increases evident in the other conditions. A statistically significant difference ($p < 0.05$) in the responses in the third and sixth minute were only evident in the most ‘ideal’ (URN) and least ‘ideal’ (RF) conditions indicating that a physiological ‘steady-state’ had only been reached in the RN and URF tasks. Energy expenditure was significantly lower ($p < 0.05$) in the least confined task (URN) compared to all other conditions. A significantly greater energy cost ($p < 0.05$) was also associated with the RF condition when compared to the RN condition. Furthermore, a lowered ceiling height (1460mm) and a reach distance of 800mm were found to have a statistically significant impact on the energy expended.

‘Central’ Rating of Perceived Exertion (CRPE) ranged from 9 (‘very light’ effort) to 12 (‘fairly light’ to ‘somewhat hard’ effort) depending on the degree of environmental constraint. Responses in the most confined task (RF) increased significantly ($p < 0.05$) from 11 (‘fairly light’ effort) in the third minute to 12 (‘fairly light’ to ‘somewhat hard’ effort) in the last minute with comparable increases in all other conditions. Mean CRPE responses were significantly higher ($p < 0.05$) in the RF condition when compared to the least constrained tasks, URN and RN. An increase in the depth of load placement was found to have a statistically significant effect (9.09%) on CRPE responses yet the effect of a decrease in the height of the ceiling was not found to significantly affect the human operator’s perception of the task.

‘Local’ Rating of Perceived Exertion (LRPE) ranged from 9 (‘very light’ physical exertion) to 11 (‘fairly light’ exertion). In all conditions, subjects reported a statistically significant difference ($p < 0.05$) in the degree to which the task taxed the musculoskeletal system in the third and sixth minute indicating that the degree of strain was progressively increasing. Mean LRPE responses were significantly greater in the RF condition when compared to the URN condition with all other conditions placing comparable demands on the subjects. Mean LRPE responses were significantly affected by a reduction in ceiling height (a 10.0% increase) and an increase in reach demands (a 9.55% increase).

The lower back was the highest rated area of discomfort in all conditions and the highest degree of discomfort was reported in the most restrictive condition (RF). Subjects rated the gluteal region as the area where the second highest amount of discomfort occurred in the restricted conditions whereas the middle and upper back were reported as experiencing the second highest amount of discomfort in the unrestricted conditions. Discomfort in the right thigh was also reported in the conditions where the load placement distance was 800mm.

STATISTICAL HYPOTHESES

It was hypothesised that the physiological and perceptual responses would be the same in all lifting conditions. In addition, it was proposed that the differences in ceiling height and reach demands would have no effect on the human operator's responses.

Hypothesis I:

a) Comparisons of the mean cardiovascular responses yielded a statistically significant difference between the responses in the least (URN) and most restricted (RF) condition. The null hypothesis was therefore rejected.

b) It was expected that all conditions would place equivalent demands on the respiratory system; however, statistically significant differences were found between mean tidal volume and mean minute ventilation responses. No statistically significant difference was evident between mean breathing frequency responses. The null hypothesis was therefore rejected for V_T and V_E and tentatively accepted for F_B.

c) There were statistically significant differences in mean oxygen consumption responses between the lifting tasks therefore the null hypothesis was rejected.

d) Comparable percentages of carbohydrates and fats were oxidised in all conditions and hence mean RQ was similar in all conditions. This null hypothesis was therefore tentatively retained.

e) Mean energy expenditure was significantly different between the lifting conditions therefore this null hypothesis was rejected.

Hypothesis II:

a) Statistically significant differences in the manner in which subjects perceived the tasks to tax the cardiovascular system (CRPE) were evident between the lifting conditions. This null hypothesis was therefore rejected.

b) The null hypothesis was rejected due to the perception that the musculoskeletal system (LRPE) was taxed to a significantly greater degree in the more restrictive tasks.

Hypothesis III:

a) The subjects’ responses were significantly greater in the conditions where the ceiling was lowered than when there was no ceiling restriction. This null hypothesis was therefore rejected for all physiological and perceptual responses except in the case of RQ and CRPE where it was tentatively accepted.

Hypothesis IV:

a) With regards to the effect of an increase in reach demands, the null hypothesis was rejected due to statistically significant increases in responses when the reach depth was 800mm compared to when it was 400mm.

CONCLUSIONS

Most of the postural, physiological and perceptual responses confirm that the lifting tasks executed with the lower ceiling height in combination with the greatest reach factor (RF), placed the most demands on the human operator. Likewise, the condition which placed the least stress on the individual was unrestricted lifting with no reach demands. However, even in this most 'ideal' condition (URN), the responses were still not ideal. For example, during lift initiation, load lifting and placement of the load, subjects experienced compression and shearing forces that are comparable to when the load was lifted in the more constrained conditions. Furthermore, working under these task parameters resulted in subjects utilising a mean energy expenditure of 24.20kJ.min^{-1} (5.78kcal.min^{-1}), which is higher than the recommended limits for extended work shifts. Although individuals performing under the most 'ideal' task (URN) parameters were exposed to unnecessary strain, perceptions of the degree to which the task taxed the cardiovascular and musculoskeletal system were low. For example, the URN task was perceived to place 'very light' to 'fairly light' strain on the cardiovascular system while the stress placed on the musculoskeletal system was considered to be 'very light' whereas the most confined task resulted in subjects experiencing 'fairly light' cardiorespiratory and musculoskeletal strain. The other two conditions (RN and URF) placed comparable demands on the subjects, suggesting that it is the interplay of task factors which ultimately determines the strain placed on the individual. However, noteworthy is that the reach demands consistently resulted in greater physiological and perceptual responses, 9.90% and 9.32% respectively, compared to ceiling restriction except when considering LRPE responses. Ultimately, however, it is the combination of these, and other factors which determine the overall strain placed on an individual within the occupational environment.

RECOMMENDATIONS

Due to the highly controlled laboratory setting within which this study was conducted, limited recommendations can be made to industry where environmental restrictions are not as tightly controlled. Furthermore, a student sample was utilised in this study which is known to affect responses as research (Legg, 1986) has identified that individuals involved in restricted tasks on a daily basis do not utilise energy to the same extent. Research should therefore be conducted *in situ* with individuals accustomed to the task demands to determine their responses.

Even though the majority of the manual workforce is male at present, a greater number of females are moving into the workforce. Future research should therefore investigate the female worker’s responses to restricted environments and whether the workloads used in this study are suitable for these individuals.

Due to the variety of tasks performed in the restricted occupational environment, different combinations of load and lifting frequency should be analysed to determine the ‘optimal’ load, frequency and load/frequency combination in these settings. Furthermore, the effect of further reductions in ceiling height and different lifting postures should be analysed.

As the human operator within the working environment performs the same task for an 8h working day, the tasks analysed during this study should be performed for a duration greater than six minutes to determine when a physiological ‘steady-state’ is achieved. The time taken for physiological drift to occur should also be investigated which in turn will identify the impact of extended work on patterns of worker fatigue.

Although guidelines exist to assess the workload that individuals are performing under, this investigation has identified that many of these guidelines are not able to differentiate between tasks with varying restrictions. Suitable guidelines for confined spaces should therefore be determined to enable industry to accurately determine when confined tasks are excessively taxing.

Due to the uniqueness of the South African workforce with regards to HIV and tuberculosis prevalence, malnutrition and poor living conditions, future investigations should attempt to quantify the workload that these individuals are exposed to. Furthermore, the impact of restricted working environments on these individuals should be considered as current assessment tools such as the NIOSH equation does not take these factors into account.

Even though images of the postures adopted during the lifting tasks were taken, the placement of the load in each image was not identical. It was therefore not possible to assess the postural effects of working in constrained spaces. This investigation therefore highlighted the manner in which the load moves from the centre of mass depending on the reach demands and presence of a barrier thereby essentially negating the effects of the lifting posture. Future investigations should therefore focus on the lifting postures specifically and the prevalence the hazardous tasks within the South African working context.

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APPENDIX A

GENERAL INFORMATION

Equipment List
Pre-Experimental/Habituation Proceedings
Do’s and Don’ts
Letter Of Information
Letter Of Informed Consent

Equipment List

- Data sheets
- Letters of information
- Letters of informed consent
- Habituation proceedings
- Test proceedings
- Pens x 10
- Subject test allocations
- Subject reminder notes
- Toledo Scale
- Stadiometer
- Chairs (6)
- K_4b^2
- Mask
- Skull cap
- Heart rate monitor
- Digital camera
- RPE scale
- Body Discomfort scale
- Ensure Rm 29 set up for practice session

Pre-Experimental Testing/Habituation

WELCOME

- Welcome my name is Amy and this is my assistant Sarah.
- Thank you so much for offering to be a subject during this research project. Your assistance is greatly appreciated.
- I am now going to go through what is required of you during this research project. Please feel free to ask questions at any time.
- Furthermore, please do not hesitate to terminate your participation in this study at any time as you are under no obligation to be a subject.
- Additionally, please be aware that at no time will you be directly identified by your data and if the data is used, it will be pooled so that your anominity is guaranteed.

AIMS OF THE RESEARCH

- This aim of this research project is three-fold. Firstly, I will be quantifying the amount of energy used in a lifting task while being performed in both restricted and unrestricted environments.
- Secondly, I will be comparing whether there is a greater energy expended while lifting in restricted or unrestricted environments.
- Thirdly, I will be quantifying the degree to which the musculoskeletal and cardiovascular system is taxed during each protocol.

EXPLANATION OF TESTING PROCEDURES

- You will be required to attend two separate testing sessions after this habituation session.
- During this session, we will record your mass, height and grip strength as well as allowing you to practise each of the lifting tasks.
- During both testing sessions you will be performing the same lifting task twice but the conditions in which you lift will change.

- Before each lift, you will be required to stand behind the demarcation and then when told to lift, you must take a step up to the load, lift the load, take a further step if required and then place the load in the required position (Demonstrate)
- The lifting task will require that you lift a crate of 12kg symmetrically once every ten seconds for six minutes (Demonstrate). A beeping sound will indicate when you have to lift the load.
- The load will either have to be placed 400mm or 800mm away from its initial position which will be demarcated with masking tape. I will allow you to practise this just now.
- An assistant will then lift and place the box back at the starting position after every lift.
- In the restricted lifting condition, the ceiling height will be lower than normal (146cm) and there will be a low barrier (55cm) in front of the crate. You will be required to lift the load over the barrier (Show this).
- In the unrestricted lifting condition, there will be no ceiling restriction but there will still be a barrier over which the load must be moved (Show this).
- Between both protocols, you will be given a rest period while the other subject completes the task.
- Any questions so far?

EQUIPMENT USED

- Quite a few pieces of equipment are going to be used during this test session so I am going to explain all of them in more detail now.

STATURE AND MASS

- Your stature and mass will be recorded during this habituation session to provide an indication of the physical variability in my subjects.

HEART RATE MONITOR

- The first and most basic piece of cardiovascular equipment that I am going to use is a heart rate monitor.
- This piece of equipment consists of a plastic band which contains electrosensors that is secured around your chest in your heart region (demonstrate). The band needs to lie directly on your skin to detect heart rate responses (Assistant to demonstrate).
- I will have to make sure that the band is attached relatively tightly around your chest to ensure that heart rate responses are recorded continuously during the test.
- I may also have to wet the band to increase the conductivity between the band and your skin which can be cold at first but the water does warm up as body heat is transferred to the strap.
- The heart rate monitor also has a watch which displays your heart rate responses. I will however not be attaching the watch during testing as you will have a heart rate probe attached to your clothing near your upper arm (show this).
- Your responses will therefore be recorded continuously on the ergospirometer which will be explained shortly.
- Any questions so far?

ERGOSPIROMETER

- As I am wanting to record the amount of energy that you use during each of the lifting tasks I will be using this machine, the Cosmed K_4b^2 (point to it) which is a portable ergospirometer to determine the amount of oxygen you consume and the amount of carbon dioxide you produce. The ratio between the two will provide me with a measure of the energy you use. I can also detect the number of breaths that you take each minute and the amount of air that you take into your lungs for example.
- This machine consists of a portable unit and battery which will be attached to your back via a harness (Show the equipment).

- There is also a mask which will cover your nose and mouth (Show mask). The mask has openings on either side to allow air into the mask so that you can breathe normally. It is attached to your face with an adjustable mesh skull cap (show skull cap). I have to tighten it slightly to prevent air from entering the mask so please let me know if you are uncomfortable.
- Finally the mask will have a gas detector attached to it. This has two tubes exiting it. These tubes carry the exhaled gases back to the portable unit located on your back which then analyses the data and sends it to the laptop which I have in front of me. I will be watching the data at all times to ensure that your responses are within range and that you are not being taxed excessively.
- While the mask is over your nose and mouth please refrain from talking and laughing as this influences your responses negatively. If you do need to communicate with us at any time, rather use hand signals such as a downward pointing thumb to indicate that I'm feeling uncomfortable and I need to stop the test.
- Any questions so far?

DIGITAL CAMERA

- We are going to be using a digital camera during the testing session to record your body posture.
- The camera will be located to your right and will not interfere with your lifting. We will be recording a single lift at the end of the third and last minute.

RATING OF PERCEIVED EXERTION (RPE)

- I am also interested in finding out how hard you perceive the lifting tasks during the two conditions to be so I am going to use a scale called the Borg's Rating of Perceived Exertion Scale (Show the scale).

- It is a numerical scale with verbal anchors ranging from 6 to 20. Each number when multiplied by 10 should be equivalent to your heart rate response during that period.
- For example, while you are sitting down like you are now you should perceive the task to be a 6 as 6 multiplied by 10 is 60bt.min^{-1} which is considered a resting heart rate.
- When performing at your maximum however, you should rate the task as a 20 which is equivalent to 200bt.min^{-1} which is your maximum heart rate.
- I will be asking for both Central RPE – how hard you think your heart and lungs are working – and Local RPE – how hard you think your muscles are working. The ratings DO NOT need to be the same and you can rate your heart and lungs as a 16 and your muscles as a 12 for example.
- You will be asked for both your Central and Local RPE twice during each lifting test: at the end of your 3rd and 6th minute. Please just point to the scale and do not talk. Sarah will confirm it with you by repeating your rating and then record it.
- Please try and estimate accurately how you are feeling during the test but be aware that there is no right or wrong answer. I want you to rate how you perceive the test.
- Do you have any questions?

BODY DISCOMFORT MAP

- The Body Discomfort Map is used so that subjects can identify regions of discomfort and the level of discomfort experienced in that specific region (Show the scale).
- The scale consists of both a front and back image of the human body which is then divided into 27 separate regions. There is also a scale at the bottom of the images which is used to identify the intensity of the discomfort felt in each region.
- The scale ranges from 1 to 10 with 1 being very mild discomfort and 10 being severe discomfort.

- At the end of each testing session, you will be required to identify three regions on the body by pointing and then point at the level of discomfort felt in each region (demonstrate this).
- Any questions?

If you have no further questions and are still interested in participating in this study, please will you read this letter of information and then sign the letter of informed consent.

Do’s and Don’t’s

For standardisation purposes please will you REFRAIN from the following for the 24 hours prior to coming into the department:

1) DRINKING ALCOHOL.

2) STRENUOUS EXERCISE.

3) IF POSSIBLE, TAKING ANY MEDICATION (such as aspirin, panado, flu tablets, pain killers, etc). IF YOU DO, PLEASE REPORT THIS TO THE RESEARCHER.

Furthermore:

4) EAT A LIGHT MEAL AT LEAST 2 HOURS BEFORE ARRIVING AT THE LABORATORY, AND THEN NOTHING FOR 90 MINUTES PRIOR TO TESTING.

Letter of Information

RHODES UNIVERSITY
DEPARTMENT OF HUMAN KINETICS AND ERGONOMICS

INFORMATION TO SUBJECTS

Dear---

Thank you for offering to participate in this study. The following pages are an explanation of the objectives of the research. This letter will inform you of what is expected of you and what procedures are going to be carried out, as well as the potential risks and benefits of your participation. Please read through this carefully and then sign the accompanying consent form.

AIM OF THE STUDY AND FUNDAMENTAL PROCEDURES

The aim of this study is to compare the responses during a lifting task in a working environment where the headroom is restricted, to the same lifting task performed in an unrestricted environment. It is hoped that this study will provide information regarding how lifting in a restricted area can affect physiological, biomechanical and perceptual responses. This information can then be used by industry to modify tasks performed in restricted environments thereby reducing the demands placed on workers.

You will be required to attend three sessions, which will last approximately 2.5 hours in total. During the first session, anthropometric data including stature, mass and grip strength will be recorded and you will be given a habituation (practise) session to familiarise yourself with the task. During both the restricted and unrestricted lifting protocols, you will be required to lift a 12kg load once every ten seconds for six minutes. During the restricted lifting task, the ceiling will be lowered to 1460mm and you will be required to lift the crate from the floor over a 554mm barrier and place the load either 400mm or 800mm away from the starting position of the load. In the unrestricted lifting task, the load and the distance across which the load is moved will remain the same but the ceiling height will not be restricted. You will be given time to familiarise yourself with each protocol before testing begins.

A heart rate monitor will be placed around your chest to measure heart rate responses over the testing period. A gas analysis machine will measure your oxygen consumption by means of a mask that is placed over your nose and mouth. Please ensure that you do not talk or laugh during the testing session as this will negatively affect the oxygen consumption results. Two minutes of resting responses will be taken, before the lifting protocol begins. A digital camera will be used to record your body posture during the lifting protocols. Your subjective perceptions of the task (how hard you feel you are working), both central (which is heart and lungs) and local (how fatigued your muscles feel) will be recorded every three minutes throughout the test. Once the test is completed, you will be required to sit for two minutes, while resting data is collected and areas of body discomfort are noted and recorded. This will enable you to communicate where you feel there is the most discomfort due to task you have just performed, and the level of discomfort experienced.

RISKS AND BENEFITS

The risks of this study involve the fact that although unlikely, there may be adverse responses to exercise, in particular cardiovascular and musculoskeletal risk. Any problems with lifting the load should be dealt with during the habituation session and any further concerns should be indicated to the researcher immediately. The utmost precautions have been taken to minimise risks, but if you do feel any nausea, dizziness, light-headedness or pain please report this immediately and the test will be terminated. You may terminate any of the tests if you feel you need to do so!

The benefits include an increased knowledge and awareness of your body's capacity for work, and in particular your oxygen consumption (energy expenditure) during physical activity. Not only will you benefit, but you will contribute to an enhanced understanding of manual materials handling in industry, and more specifically how restricted working environments impact workers' responses.

Please feel free to ask any questions with regard to the study and the procedures you will be following. Remember that you are free to withdraw at any time. Should you be interested, I will gladly discuss your test results once all the subjects have been tested. Thank you again for volunteering to be a subject in my study.

Yours sincerely

Amy Wolfe
(MSc student – Department of Human Kinetics and Ergonomics)

Letter of Informed Consent

RHODES UNIVERSITY
DEPARTMENT OF HUMAN KINETICS AND ERGONOMICS
INFORMED CONSENT

I, ---, having been fully informed of the research entitled: '**The effect of ceiling restriction and lifting barriers on selected postural, physiological and perceptual responses**' 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 associated with my participation, as explained to me verbally and in writing. In agreeing to participate in this study, I waive any legal recourse against the researcher or Rhodes University, in the event of any personal injuries sustained. This waiver shall be binding upon my heirs and legal representatives.

I realise the necessity to promptly report to the researcher any signs or symptoms indicating any abnormality or distress and I am fully aware that I may withdraw from participation in the study at any time. I am aware that my anonymity will be protected at all times, and agree that the information collected may be used and published for statistical or scientific purposes.

I have read, and understood, the information sheet accompanying this form. Any queries I have had have been answered to my satisfaction.

______________________	________	___________
(PRINT NAME) SUBJECT	**SIGNED**	**DATE**
______________________	________	___________
(PRINT NAME) WITNESS	**SIGNED**	**DATE**
______________________	________	___________
(PRINT NAME) RESEARCHER	**SIGNED**	**DATE**

APPENDIX B

DATA COLLECTION

Test Session Proceedings
Equipment List
Rating of Perceived Exertion Scale
Body Discomfort Map And Scale
Data Collection Sheets

Test Session Proceedings

Pre-testing

1. Put heaters on
2. Set up Cosmed K4b^2 an hour before testing commences and ensure that its calibrated
3. Put out all equipment
4. Set up beeper
5. Sms/text subjects to remind about testing
6. Inform Candice when testing
7. Remind helpers about testing

Testing

1. Ask subject if have been drinking; had good meal; medication ingestion; flu etc
2. Ask about any injuries
3. Ask subject if they remember how to perform the task
4. Go over the task (tell subject whether they will be completing the restricted or unrestricted tasks)
5. Ask subject if they have any further questions
6. Put on HR monitor
7. Get subject seated
8. Put on skull cap and mask
9. Put on Cosmed K4b^2 plus harness etc
10. Record 2 mins of resting data
11. Test subject
12. Ask RPE during testing
13. Take images during testing
14. Take body discomfort after testing
15. Ask for any other info that would like to contribute
16. Thank subject for assistance
17. Test next subject

Equipment List

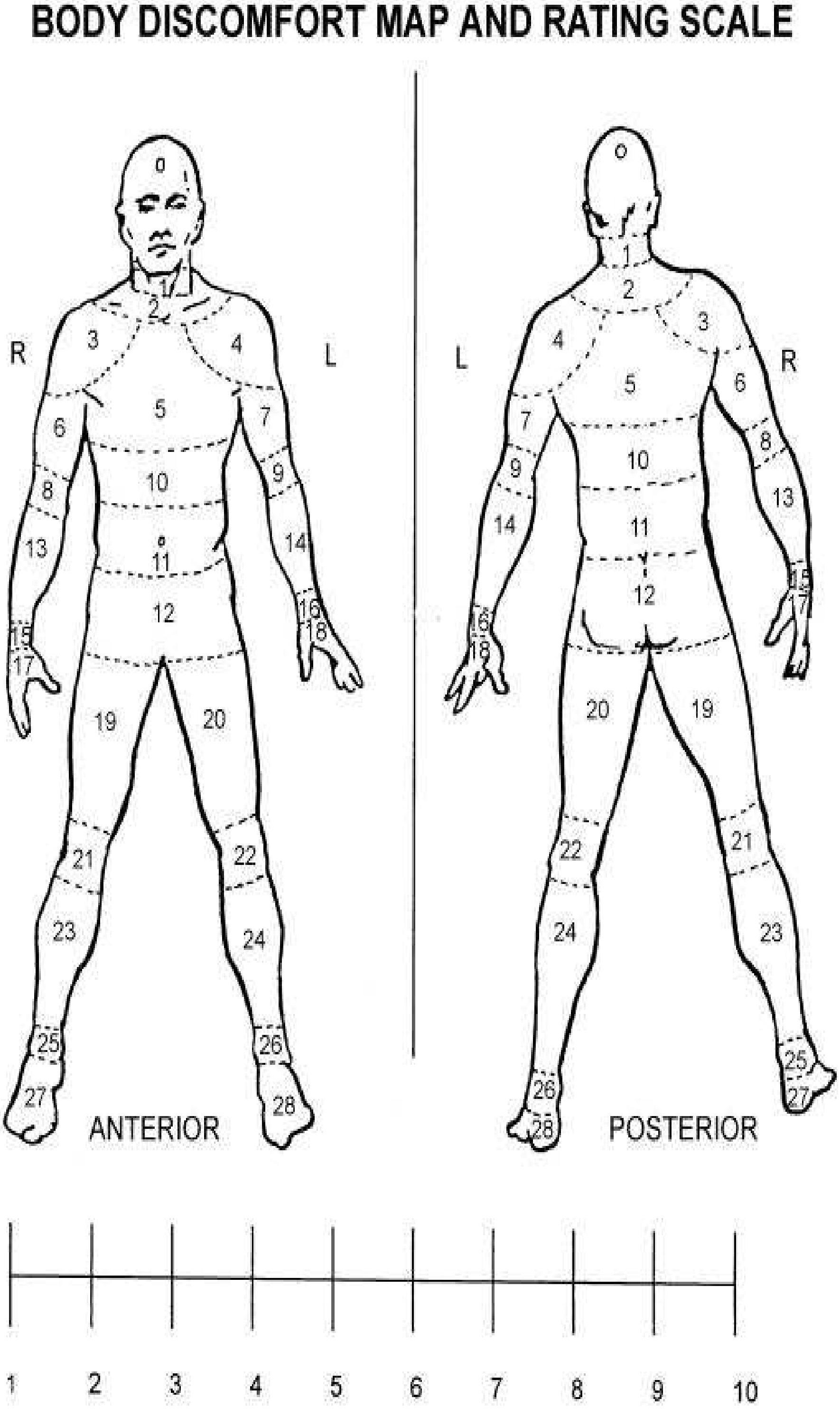
- Cosmed K4b^2
- Digital camera
- Laptop
- Heart rate monitor
- Masks
- Skull cap
- RPE
- Body Discomfort
- Pen
- Data sheets
- Load
- Sarah
- Helpers
- Next session sheet
- Next session slips
- Tripod
- Heaters
- Medical tape
- Data file
- Cup of water

Rating of Perceived Exertion Scale

RPE SCALE

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

Body Discomfort Map and Scale



RESTRICTED LIFTING TASK

NAME: ______________________________

CODE: ______________________________

DATE OF BIRTH (AGE): ____________________

MASS: ______________________________

STATURE: ____________________________

GRIP STRENGTH: ____________________(L) DOMINANT HAND: L / R

____________________(R)

ANTICIPATORY HR: ____________________

LOWER BACK / UPPER BODY INJURY IN LAST 6 MONTHS:

____

RESTRICTED CLOSE (400MM)

	RPE					
TIME (min)	CENTRAL	LOCAL	HEART RATE (bt.min^{-1})	VO$_2$ (ml.min^{-1}.kg^{-1})	CYCLE TIME (sec)	COMMENTS
1						
2						
3						
4						
5						
6						

BODY DISCOMFORT

	ANTERIOR/POSTERIOR	AREA	RATING
1ST	A/P		
2ND	A/P		
3RD	A/P		

RESTRICTED FAR (800MM)

	RPE					
TIME (min)	CENTRAL	LOCAL	HEART RATE (bt.min^{-1})	VO$_2$ (ml.min^{-1}.kg^{-1})	CYCLE TIME (sec)	COMMENTS
1						
2						
3						
4						
5						
6						

BODY DISCOMFORT

	ANTERIOR/POSTERIOR	AREA	RATING
1ST	A/P		
2ND	A/P		
3RD	A/P		

APPENDIX C

ANOVA TABLES

One Way ANOVAS

Two Way ANOVAS

One Way ANOVAS

Univariate Tests of Significance for Mean HR (min3to6) (Mean min3-6 HR da
Sigma-restricted parameterization
Effective hypothesis decomposition

Effect	SS	Degr. of Freedom	MS	F	p
Intercept	1582301	1	1582301	8338.684	0.000000
Condition	1637	3	546	2.875	0.038932
Error	23530	124	190		

Tukey HSD test; variable Mean HR (min3to6) (Mean min3-6 HR dat
Approximate Probabilities for Post Hoc Tests
Error: Between MS = 189.75, df = 124.00

Cell No.	Condition	{1} 106.11	{2} 109.77	{3} 113.33	{4} 115.52
1	1		0.713422	0.154270	0.031999
2	2	0.713422		0.728603	0.339185
3	3	0.154270	0.728603		0.920614
4	4	0.031999	0.339185	0.920614	

Univariate Tests of Significance for Mean FB min3-6 (Breathing responses data for ANOV
Sigma-restricted parameterization
Effective hypothesis decomposition

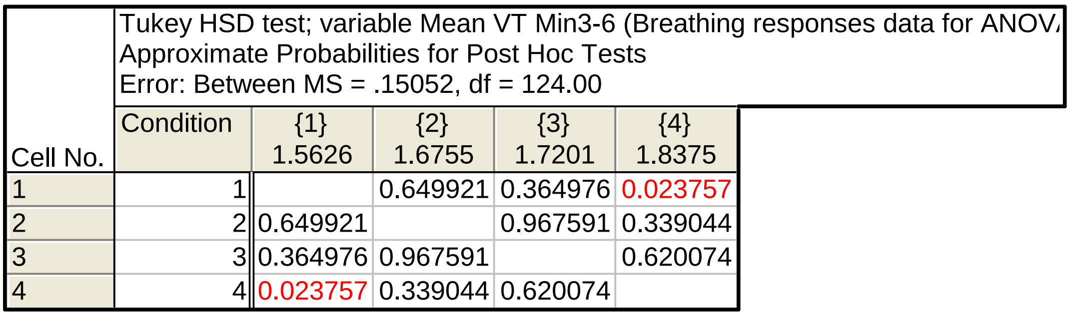
Effect	SS	Degr. of Freedom	MS	F	p
Intercept	48012.67	1	48012.67	3341.450	0.000000
Condition	10.29	3	3.43	0.239	0.869216
Error	1781.73	124	14.37		

Tukey HSD test; variable Mean FB min3-6 (Breathing responses data for ANOV
Approximate Probabilities for Post Hoc Tests
Error: Between MS = 14.369, df = 124.00

Cell No.	Condition	{1} 18.918	{2} 19.373	{3} 19.489	{4} 19.691
1	1		0.963419	0.931203	0.847104
2	2	0.963419		0.999347	0.987044
3	3	0.931203	0.999347		0.996598
4	4	0.847104	0.987044	0.996598	

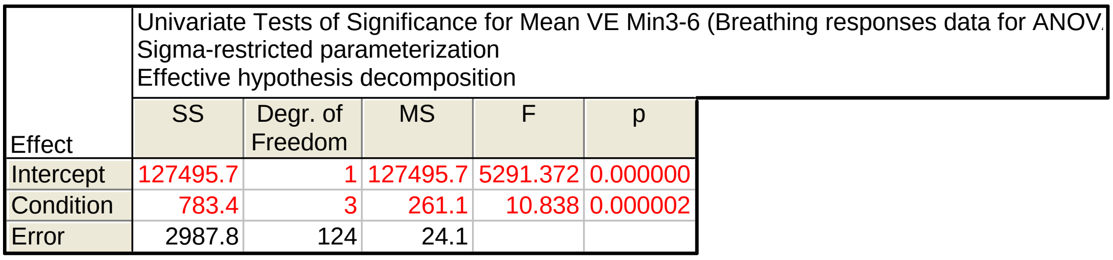
Univariate Tests of Significance for Mean VT Min3-6 (Breathing responses data for ANOV
Sigma-restricted parameterization
Effective hypothesis decomposition

Effect	SS	Degr. of Freedom	MS	F	p
Intercept	369.4538	1	369.4538	2454.506	0.000000
Condition	1.2416	3	0.4139	2.749	0.045649
Error	18.6646	124	0.1505		



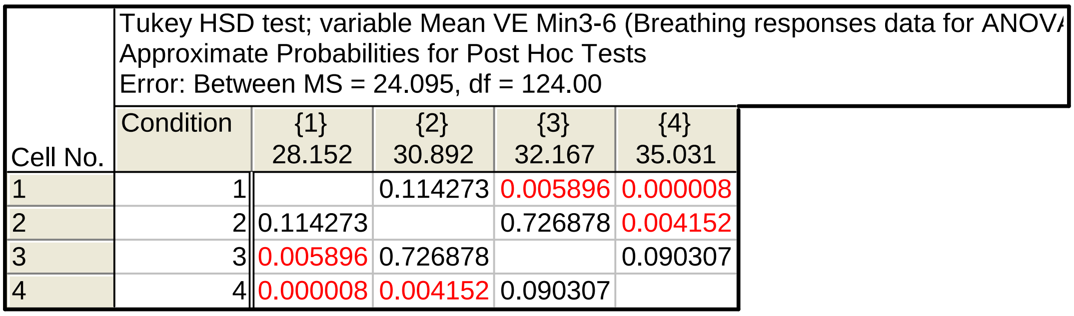
Tukey HSD test; variable Mean VT Min3-6 (Breathing responses data for ANOV
Approximate Probabilities for Post Hoc Tests
Error: Between MS = .15052, df = 124.00

Cell No.	Condition	{1} 1.5626	{2} 1.6755	{3} 1.7201	{4} 1.8375
1	1		0.649921	0.364976	0.023757
2	2	0.649921		0.967591	0.339044
3	3	0.364976	0.967591		0.620074
4	4	0.023757	0.339044	0.620074	



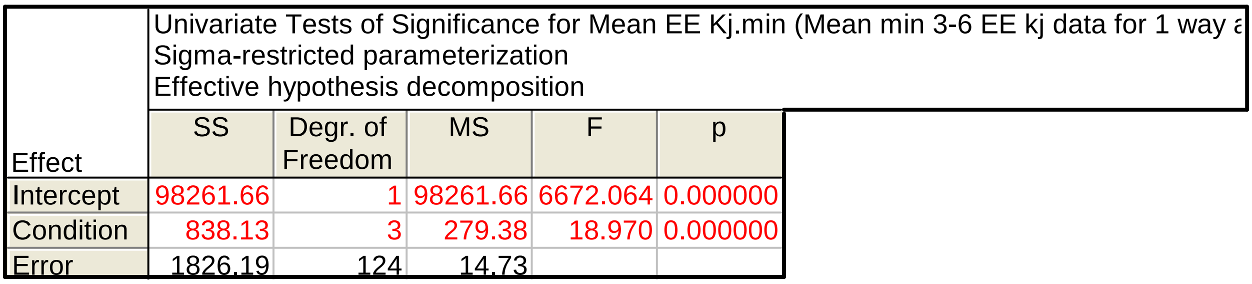
Univariate Tests of Significance for Mean VE Min3-6 (Breathing responses data for ANOV
Sigma-restricted parameterization
Effective hypothesis decomposition

Effect	SS	Degr. of Freedom	MS	F	p
Intercept	127495.7	1	127495.7	5291.372	0.000000
Condition	783.4	3	261.1	10.838	0.000002
Error	2987.8	124	24.1		



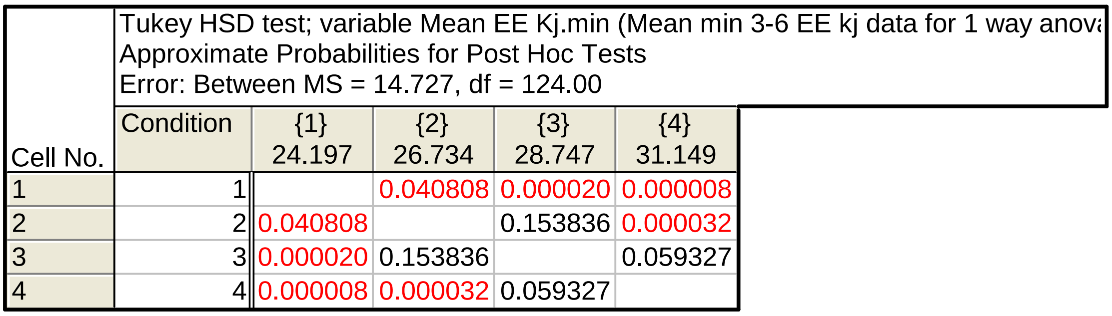
Tukey HSD test; variable Mean VE Min3-6 (Breathing responses data for ANOV
Approximate Probabilities for Post Hoc Tests
Error: Between MS = 24.095, df = 124.00

Cell No.	Condition	{1} 28.152	{2} 30.892	{3} 32.167	{4} 35.031
1	1		0.114273	0.005896	0.000008
2	2	0.114273		0.726878	0.004152
3	3	0.005896	0.726878		0.090307
4	4	0.000008	0.004152	0.090307	



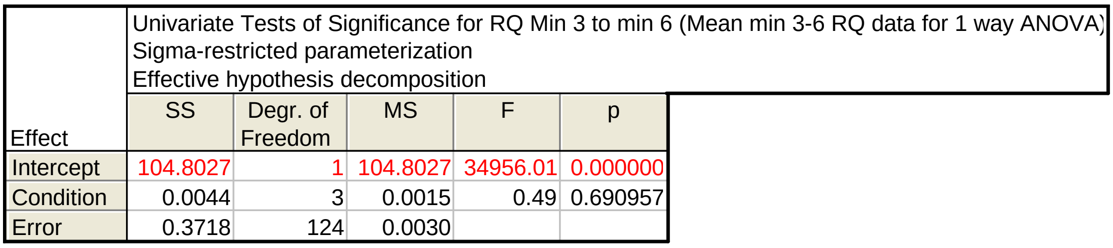
Univariate Tests of Significance for Mean EE Kj.min (Mean min 3-6 EE kj data for 1 way
Sigma-restricted parameterization
Effective hypothesis decomposition

Effect	SS	Degr. of Freedom	MS	F	p
Intercept	98261.66	1	98261.66	6672.064	0.000000
Condition	838.13	3	279.38	18.970	0.000000
Error	1826.19	124	14.73		

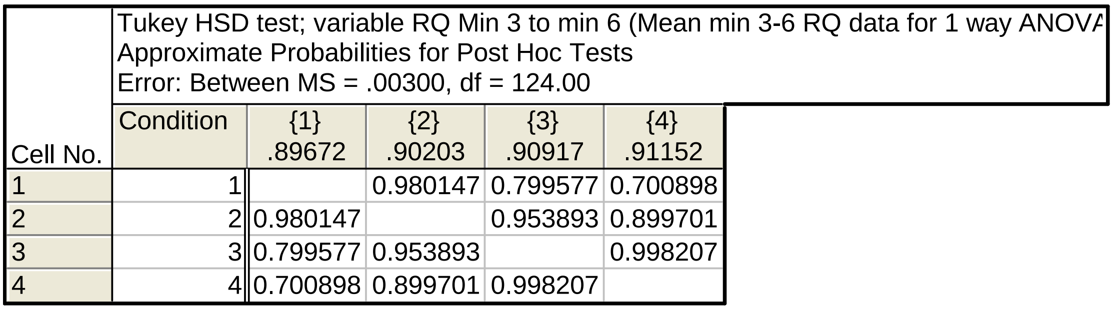


Tukey HSD test; variable Mean EE Kj.min (Mean min 3-6 EE kj data for 1 way anov
Approximate Probabilities for Post Hoc Tests
Error: Between MS = 14.727, df = 124.00

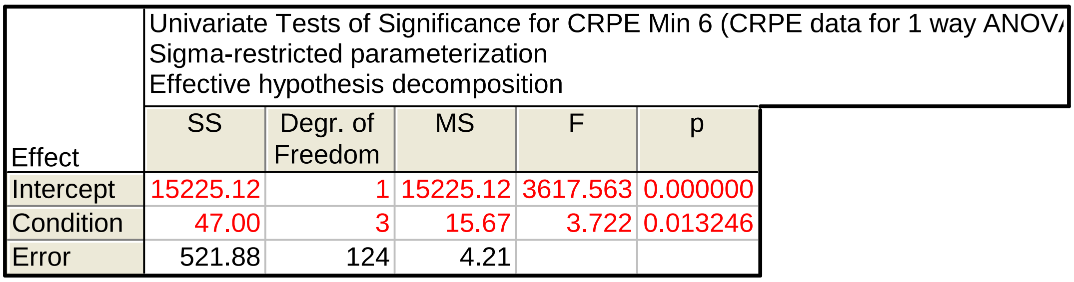
Cell No.	Condition	{1} 24.197	{2} 26.734	{3} 28.747	{4} 31.149
1	1		0.040808	0.000020	0.000008
2	2	0.040808		0.153836	0.000032
3	3	0.000020	0.153836		0.059327
4	4	0.000008	0.000032	0.059327	


Univariate Tests of Significance for RQ Min 3 to min 6 (Mean min 3-6 RQ data for 1 way ANOVA)
Sigma-restricted parameterization
Effective hypothesis decomposition

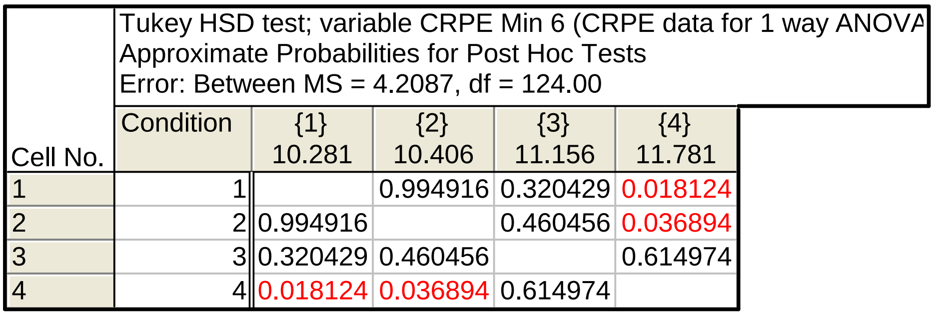
Effect	SS	Degr. of Freedom	MS	F	p
Intercept	104.8027	1	104.8027	34956.01	0.000000
Condition	0.0044	3	0.0015	0.49	0.690957
Error	0.3718	124	0.0030		


Tukey HSD test; variable RQ Min 3 to min 6 (Mean min 3-6 RQ data for 1 way ANOV
Approximate Probabilities for Post Hoc Tests
Error: Between MS = .00300, df = 124.00

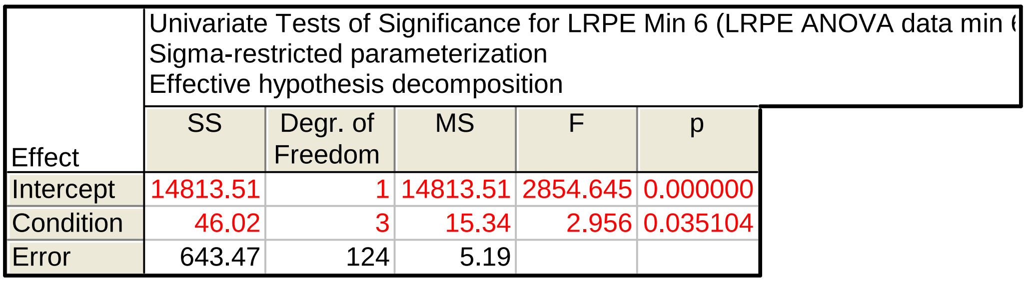
Cell No.	Condition	{1} .89672	{2} .90203	{3} .90917	{4} .91152
1	1		0.980147	0.799577	0.700898
2	2	0.980147		0.953893	0.899701
3	3	0.799577	0.953893		0.998207
4	4	0.700898	0.899701	0.998207	


Univariate Tests of Significance for CRPE Min 6 (CRPE data for 1 way ANOV
Sigma-restricted parameterization
Effective hypothesis decomposition

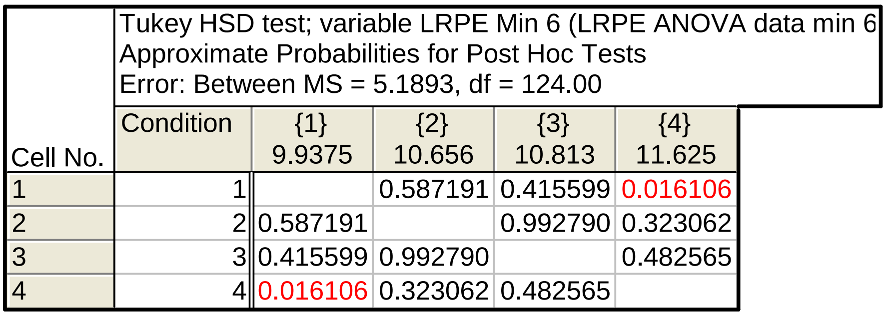
Effect	SS	Degr. of Freedom	MS	F	p
Intercept	15225.12	1	15225.12	3617.563	0.000000
Condition	47.00	3	15.67	3.722	0.013246
Error	521.88	124	4.21		


Tukey HSD test; variable CRPE Min 6 (CRPE data for 1 way ANOV
Approximate Probabilities for Post Hoc Tests
Error: Between MS = 4.2087, df = 124.00

Cell No.	Condition	{1} 10.281	{2} 10.406	{3} 11.156	{4} 11.781
1	1		0.994916	0.320429	0.018124
2	2	0.994916		0.460456	0.036894
3	3	0.320429	0.460456		0.614974
4	4	0.018124	0.036894	0.614974	


Univariate Tests of Significance for LRPE Min 6 (LRPE ANOVA data min
Sigma-restricted parameterization
Effective hypothesis decomposition

Effect	SS	Degr. of Freedom	MS	F	p
Intercept	14813.51	1	14813.51	2854.645	0.000000
Condition	46.02	3	15.34	2.956	0.035104
Error	643.47	124	5.19		



Tukey HSD test; variable LRPE Min 6 (LRPE ANOVA data min 6
Approximate Probabilities for Post Hoc Tests
Error: Between MS = 5.1893, df = 124.00

Cell No.	Condition	{1} 9.9375	{2} 10.656	{3} 10.813	{4} 11.625
1	1		0.587191	0.415599	0.016106
2	2	0.587191		0.992790	0.323062
3	3	0.415599	0.992790		0.482565
4	4	0.016106	0.323062	0.482565	

Two Way ANOVAS

	Repeated Measures Analysis of Variance (HR Min 6 data.sta Sigma-restricted parameterization Effective hypothesis decomposition				
Effect	SS	Degr. of Freedom	MS	F	p
Intercept	1641154	1	1641154	2245.935	0.000000
Error	22652	31	731		
ENVIRON	344	1	344	5.602	0.024368
Error	1905	31	61		
REACH	1762	1	1762	119.141	0.000000
Error	459	31	15		
ENVIRON*REACH	12	1	12	1.229	0.276162
Error	303	31	10		

	Repeated Measures Analysis of Variance (VO2 Min 6 data.sta Sigma-restricted parameterization Effective hypothesis decomposition				
Effect	SS	Degr. of Freedom	MS	F	p
Intercept	37910.41	1	37910.41	3031.801	0.000000
Error	387.63	31	12.50		
ENVIRON	73.34	1	73.34	11.546	0.001882
Error	196.92	31	6.35		
REACH	237.13	1	237.13	155.315	0.000000
Error	47.33	31	1.53		
ENVIRON*REACH	0.49	1	0.49	0.494	0.487304
Error	30.65	31	0.99		

	Repeated Measures Analysis of Variance (Breathing freq Min 6 data.st Sigma-restricted parameterization Effective hypothesis decomposition				
Effect	SS	Degr. of Freedom	MS	F	p
Intercept	49271.93	1	49271.93	966.8954	0.000000
Error	1579.73	31	50.96		
ENVIRON	17.51	1	17.51	2.5616	0.119634
Error	211.87	31	6.83		
REACH	27.20	1	27.20	7.3836	0.010673
Error	114.20	31	3.68		
ENVIRON*REACH	0.78	1	0.78	0.4492	0.507693
Error	53.93	31	1.74		

Repeated Measures Analysis of Variance (Tidal vol Min 6 data.st
Sigma-restricted parameterization
Effective hypothesis decomposition

Effect	SS	Degr. of Freedom	MS	F	p
Intercept	384.9059	1	384.9059	761.5555	0.000000
Error	15.6680	31	0.5054		
ENVIRON	0.3111	1	0.3111	3.2978	0.079056
Error	2.9244	31	0.0943		
REACH	0.5524	1	0.5524	14.8224	0.000553
Error	1.1552	31	0.0373		
ENVIRON*REACH	0.0081	1	0.0081	0.6052	0.442492
Error	0.4174	31	0.0135		

Repeated Measures Analysis of Variance (Minute ventilation Min 6 data.st
Sigma-restricted parameterization
Effective hypothesis decomposition

Effect	SS	Degr. of Freedom	MS	F	p
Intercept	136924.7	1	136924.7	1885.284	0.000000
Error	2251.5	31	72.6		
ENVIRON	317.6	1	317.6	11.669	0.001793
Error	843.8	31	27.2		
REACH	652.8	1	652.8	102.259	0.000000
Error	197.9	31	6.4		
ENVIRON*REACH	0.7	1	0.7	0.166	0.686884
Error	122.3	31	3.9		

Repeated Measures Analysis of Variance (RQ Min 6 data.sta
Sigma-restricted parameterization
Effective hypothesis decomposition

Effect	SS	Degr. of Freedom	MS	F	p
Intercept	114.4387	1	114.4387	33112.74	0.000000
Error	0.1071	31	0.0035		
ENVIRON	0.0045	1	0.0045	1.08	0.306056
Error	0.1290	31	0.0042		
REACH	0.0156	1	0.0156	17.15	0.000246
Error	0.0281	31	0.0009		
ENVIRON*REACH	0.0003	1	0.0003	0.38	0.542638
Error	0.0223	31	0.0007		

	Repeated Measures Analysis of Variance (CRPE Min 6 data-1.sta Sigma-restricted parameterization Effective hypothesis decomposition				
Effect	SS	Degr. of Freedom	MS	F	p
Intercept	15225.12	1	15225.12	1057.360	0.000000
Error	446.38	31	14.40		
ENVIRON	4.50	1	4.50	4.103	0.051491
Error	34.00	31	1.10		
REACH	40.50	1	40.50	62.775	0.000000
Error	20.00	31	0.65		
ENVIRON*REACH	2.00	1	2.00	2.884	0.099497
Error	21.50	31	0.69		

	Repeated Measures Analysis of Variance (LRPE Min 6 data.sta Sigma-restricted parameterization Effective hypothesis decomposition				
Effect	SS	Degr. of Freedom	MS	F	p
Intercept	14813.51	1	14813.51	913.4279	0.000000
Error	502.74	31	16.22		
ENVIRON	18.76	1	18.76	7.6020	0.009684
Error	76.49	31	2.47		
REACH	27.20	1	27.20	22.1538	0.000050
Error	38.05	31	1.23		
ENVIRON*REACH	0.07	1	0.07	0.0833	0.774850
Error	26.18	31	0.84		

	Repeated Measures Analysis of Variance (CRPE Min 6 data-1.sta Sigma-restricted parameterization Effective hypothesis decomposition				
Effect	SS	Degr. of Freedom	MS	F	p
Intercept	15225.12	1	15225.12	1057.360	0.000000
Error	446.38	31	14.40		
ENVIRON	4.50	1	4.50	4.103	0.051491
Error	34.00	31	1.10		
REACH	40.50	1	40.50	62.775	0.000000
Error	20.00	31	0.65		
ENVIRON*REACH	2.00	1	2.00	2.884	0.099497
Error	21.50	31	0.69		