The Effect of Varying Work Order Sequences on Physiological Responses in Combined Manual Material Handling

by

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Abstract

Despite technological advances in the workplace that reduces the physical requirements of the worker, musculoskeletal disorders (MSDs) continue to be a concern. This is particularly the case in the manual material handling (MMH) industry. Although a considerable amount of effort has been made to address injury occurrences in MMH, such as the development of guidelines for a vast range of physiological, psychophysical, and biomechanical responses, these efforts fall short of understanding and encompassing all the complex characteristics of real world MMH jobs. One such characteristic is the variation in work intensity while performing combined manual material handling (CMMH) activities. This is often seen in occupations such as warehouse distribution order picking where loads of drastically different weights must be handled in a stochastic pattern. Research has shown that fatigue, both whole-body and localized muscle fatigue, is an important factor that should be considered in the effort to minimize the occurrence of MSDs. However, little is known about the impact workload variation has on the physiological responses that have been used as basis of designing work to control fatigue and injuries; responses such as heart rate, heart rate kinetics, RPE, and energy expenditure. It is also unclear how this variation affects localized trunk muscle fatigue development and activity; a relatively new but increasing research area for lower intensity repetitive MMH work for its noted relationship to the potential development of back MSDs. Therefore, more understanding of these responses in this type of MMH work was warranted. The purpose of this body of research contained herein was to

initiate the discussion on and begin investigations of these responses that account for this type of operation. Furthermore, in an effort to mimic real world situations as much as possible, the research was designed to further encompass combined manual material handling (CMMH); another significant aspect of MMH that is limited in terms of research focus. Thus, this work expanded on that research area as well.

The first study sought to determine if initiating and altering the intensity of a previous (baseline) workload in a simulated order picking task had an effect on the various physiological responses of a subsequent workload. It also sought to determine if these responses were affected if the order of the workload sequence was re-arranged. The results of the study suggested that a previous workload of very low to moderate intensity would have no significant impact on heart rate related responses of a subsequent load. The results also suggested that reordering the sequence order of very low to moderate intensity workloads does not significantly impact the overall heart rate related responses of the task.

Because it was speculated that the insignificant differences found in the first study was due to the relatively low level of work intensities evaluated, a second study was conducted to evaluate the impact workload sequence order had on the physiological responses in a higher intensity simulated order picking scenario that included lifting and lowering from low levels and higher weights. An additional objective was to determine the applicability of traditional energy prediction models in MMH work involving varying workloads. The results of this study suggested that in higher intensity work, sequence order does affect the heart rate related responses of the work sequences as well as the whole-body perceived exertion of the individual workloads within the respective sequences. The conflicting magnitude of the results, however, suggested that the response could be dependent upon specific dose-response characteristics. The results of the study furthermore suggested that sequence order need not be considered when energy expenditure prediction models are utilized.

The final study was conducted to examine the effects varying the workload sequence order had on the static and dynamic fatigue development and muscle activity in localized trunk muscles. The surface EMG and rated perceived exertion results of the study suggested that muscle activity of select trunk muscles reacted significantly different in the various sequence orders but muscle fatigue, either static or dynamic, was not found to be affected. This suggested that muscle activity may be a more important factor when evaluating work ordering.

The overall conclusion of this body of research was that work variation in the form of workload sequence order in MMH work does have an impact on the various physiological responses. Research on additional MMH work variation characteristics (e.g., varied workload picking durations or pick locations) should be considered to further enhance the understanding of this type of work to possibly aid in developing work ordering optimization techniques and design guidelines to minimize worker fatigue and thus the potential occurrence of MSDs in the industry.

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CHAPTER ONE

INTRODUCTION

Work related musculoskeletal disorders (MSDs) such as tendonitis and low back pain have long been a serious issue in terms of both the economic toll and human suffering it ensues and it continues to be an issue today. In terms of the financial burden, it has been reported that MSDs have an annual estimated cost ranging anywhere from as much as $54 billion (National Institute of Occupational Safety and Health [NIOSH], 2001) to a staggering $850 billion (American Academy of Orthopaedic Surgeons 2008). Recent injury data reflect the ongoing prevalence of MSDs in the workforce. According to the U.S. Bureau of Labor Statistics [BLS], 335,390 MSDs were reported in 2007 for all private industries, accounting for approximately 29% of all 1.2 million injuries recorded. This equated to an overall private industry rate of 35 per 10,000 full-time workers (BLS, 2009a). In terms of the reported cause or event of injuries in 2007, ‘Overexertion’ (including ‘Overexertion while lifting’) and ‘Repetitive Motion’ accounted for 26% (BLS, 2009b), with injuries involving the trunk (including the back and shoulder) totaling 384,650 (235,960 and 75,580 for back and shoulder, respectively) and was the most reported body part affected (BLS, 2009b).

Although MSDs are found in almost every industry, they are highly prevalent in Manual Material Handling (MMH), particularly MSDs of the back. By its very nature, MMH jobs require manual manipulation of material, such as pushing, pulling, lifting, lowering, and carrying, which can be very taxing on the musculoskeletal and cardiopulmonary systems of the human body. In a physical MMH work system, an imbalance that favors the needs of the work task, environment, or tools over human capabilities can lead to worker pain and suffering as the worker must tolerate this imbalance if the system is to remain in operation (Ayoub & Mital, 1989). Even though recent advances in MMH technology, including advances in automation and the wide spread use of material handling equipment, has done much to address and ensure this system balance, ergonomically related injuries continue to be significant in the MMH industry. According to the BLS (2009a), 'Laborers and freight, stock, and material movers' experienced the highest number of days-away-from-work cases, with 79,000 in 2007" and the MSD rate for this occupation was 149 cases per 10,000 full-time workers (Figure 1).

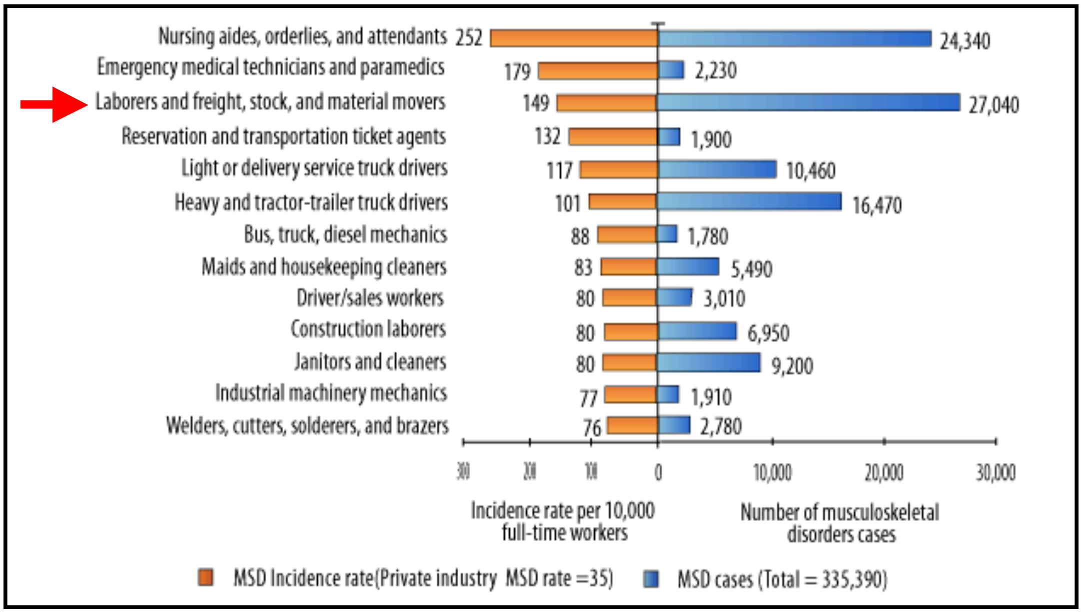


Figure 1: Incidence rates per 10,000 full-time workers and number of injuries and illnesses requiring days away from work due to musculoskeletal disorders, selected occupations, 2007 (Taken from BLS, 2009a)

It is apparent that there is still ample opportunity to further improve the safety of MMH tasks. Ensuring work demands do not exceed the physical capabilities is necessary to improving the safety of these tasks. Job (re)design is the most effective method to create this balance when the physiological response to the work is taken into account. One potential aid in developing safe and efficient MMH job designs is the use of operation research scheduling theory to optimize MMH tasks with the objective of minimizing adverse human responses that could potentially lead to an injury, such as excessive fatigue or high levels of biomechanical spinal loading. The incorporation of ergonomic factors into scheduling theory is fairly recent, with past derived algorithms focusing mainly only on optimizing task precedence and cycle time duration (Carnahan, Norman, & Redfern, 2001). However, as noted by Lodree, Geiger, and Jiang (2009), scheduling literature has recently evolved such that modeled human characteristics, both physical and cognitive, can be taken into account within the scheduling theory framework.

One particular scheduling problem discussed by Lodree et al. (2009) was human task-sequencing. This is where the sequence of the tasks presented to the operator must be completed such that performance criteria are optimized. One occupation within the MMH industry that could possibly benefit from the use of this optimization task scheduling is warehouse distribution order picking. Order picking is the fulfillment of outbound customer order requests by way of manually retrieving goods stored within warehouses and distribution centers. Depending on the nature of the operation, these good requests can vary considerably in terms of characteristics (shape, size, weight), storage location, and retrieval requirements; thereby dictating the order picking method such as single piece, case, or pallet picking. Although a number of equipment options are available to aid in the picking process, including forklifts, automatic storage and retrieval systems (ASRS), automatic picking machines, and automated conveyor and sortation systems, the most common method of storage within these centers is static shelving (Piasecki, 2001), which does not lend itself easily to the use of such equipment. Therefore order picking is often a labor intensive operation, with pickers faced with the task of repetitively lifting, lowering, and carrying products which is work that, depending on the order assignment, can vary significantly in work intensity as well as drastically in terms of duration within the pick. This is the case for the Big Lots Distribution Center of Montgomery, AL. At this center, order pickers pick cases of products from pallets and place them on an outbound conveyor per a given assignment as determined by customer (store) stocking needs. Given the stores carry and sell a huge variety of products, from small food items to bulky dog food, these cases can vary a great deal in size and weight.

Pallets are stored floor level in individual slots on 4-tiered mezzanines and are replenished as needed (see Figures 2 and 3 for a top and side view depiction of order picking at the Big Lots DC).

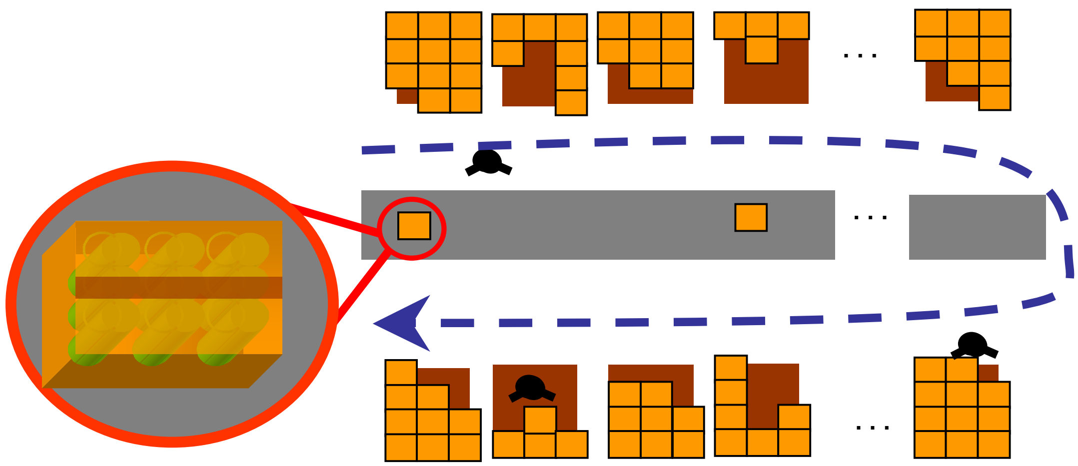


Figure 2: Illustration of the top view of BLDC picking mezzanine (not to scale)

Slot 1	**Slot 2**	**Slot 3**	**Slot 4**	**Slot 5**	**Slot 6**	**Slot 7**	**. . .**	**Slot 42**
5 lbs	**13 lbs**	**2 lbs**	**35 lbs**	**2 lbs**	**52 lbs**	**29 lbs**		**10 lbs**

Figure 3: Illustration of the side view of BLDC picking mezzanine (not to scale; Weights are for illustration only). Each slot represents a different product with varying load characteristics.

Order picking assignments, which is essentially a ‘shopping list’ of requested products, lends itself to the concept and benefits of human task-sequencing in that, in theory, orders could easily be rearranged as dictated by the scheduling algorithm. Considering the significant physical demands required in order picking, optimizing the pick order sequence such that worker fatigue, both whole-body and localized muscle, is minimized and/or kept below recommended physiological capacities and guidelines (i.e., maximum of 33% Maximum Aerobic Capacity for an 8 hour work day (Ayoub & Mital, 1989)) is ideal. However, understanding and incorporating expected physiological responses of the unstable work intensity nature of order picking to be assessed against said guidelines and to compare feasible solutions amongst themselves is paramount to determine optimal schedules. It is this unstable nature, the continuous alternating of work rates and intensities, compounded with the inherent static and dynamic physical loading seen with MMH activities, that present several issues when determining optimal sequences for order picking. Those include:

1) Understanding the impact that the work intensity sequence has on physiological responses in MMH tasks is unclear per the available research to date, which is expanded upon in the literature review provided in Chapter Two of this dissertation. Although extensive research has been conducted on MMH activities and their varied impact on fatigue as dependent on such factors as frequency, weight of load, posture, and distance (Aquilano, 1968; Ayoub & Mital, 1989; Chaffin & Anderson, 1991; Garg & Herrin, 1979; Grandjean, 1988; Hamilton & Chase, 1969; Mital & Asfour, 1983; Putz-Anderson, 1988), the effect changing work intensity order within the same MMH job, particularly with respect to local muscle fatigue, has not been examined. More specifically, this

effect has not been examined in combined manual material handling (CMMH) activities, which is where single MMH activities are performed in various combinations. CMMH is highly prevalent in order picking.

2) Comparison of the fatigue performance outcome of potential sequences as derived via scheduling would prove ineffective with current prediction models and tools. As noted by Dempsey & Mathiassen (2006), MMH jobs are often assessed by separating complex situations into individual tasks or elements. With task-based analyses, the total job fatigue burden of a grouping of activities rely on the additive assumption, or the summation of the expected net steady-state metabolic cost for the sequential individual tasks, as proposed by Garg, Chaffin, & Herrin (1978). By design, this approach is not useful in comparing sequences if the objective function of the task-sequencing scheduling algorithm is to minimize fatigue. Furthermore, although this approach is highly used for assessing the physiological cost of CMMH activities, its accuracy with regard to CMMH has been disputed by others (Taboun & Dutta, 1989). Therefore, it is not clear whether the summation approach would be applicable in this CMMH alternating work intensity scenario.

3) As with the afore mentioned comparison concern, the available research and models do not lend themselves to robust and real-time assessment of fatigue accumulation for this CMMH activity. This is mainly due to the lack of research on the varying fatigue rates that could be utilized in recursive prediction models and in turn aid in developing optimal schedules as well as optimal work-rest schedules for order picking assignments, if applicable.

Therefore, the aim of this body research is to contribute to the pool of knowledge as it pertains to MMH, more specifically CMMH activities that change significantly and drastically in work intensities as seen with order picking jobs as well as other parcel loading and unloading occupations. The research to be included in this dissertation will investigate of the impact of sequencing varying workloads on physiological responses. The physiological impact will include a focus on both whole-body and localized muscle fatigue, as both are influenced in CMMH activities and could both serve as critical inputs into an optimization model. Furthermore, it is the goal of this research to provide verification of the applicability of the additive assumption of this CMMH activity and the varying work intensity scenario.

Format of the Dissertation

The manuscript format is used in the organization of this dissertation. As a result, separate manuscript chapters encompass the body of the dissertation. An overall introduction is presented in this chapter and a comprehensive literature review follows in Chapter Two. Relevant literature is also provided within each of the three following manuscripts. Chapters Three, Four, and Five are stand-alone manuscripts detailing studies designed to evaluate the effects varying manual material handling work tasks has on the development of both whole-body and localized trunk muscle fatigue. Chapter Three outlines the experiment developed to evaluate work intensity sequence's impact on the heart rate kinetics while performing low to moderate intensity simulated order picking. The study within this Chapter also evaluates the effect the level of previous work intensity has on the fatigue indexes of a following work load. Chapter Four discusses the study developed to investigate whole-body fatigue development and energy expenditure while performing lifting, lowering, and carrying activities in varying work intensity sequences. Chapter Five details a similar study which evaluates fatigue development and activity of select trunk muscles during lifting, lowering, and carrying activities, again while varying work intensity sequences. The conclusions and recommendations developed as a result of this entire body of research are presented in Chapter Six.

CHAPTER TWO

REVIEW OF LITERATURE

Introduction

Ergonomics, as defined by the International Ergonomics Association [IEA], is

"…the scientific discipline that focuses on the interaction between humans and work within a system. It utilizes the knowledge of principles, theories, methods and data to optimize human well-being and overall system performance" (IEA, 2000).

This optimization requires a balance between the capabilities of the human being, be it physical or mental, the surrounding environment, applicable equipment and tools, and the requirements of the work task. When there is a failure to meet this balance, system performance can become inefficient and/or ineffective. A manual material handling, or MMH, system follows the same suit. The approach to maintain system integrity here has been to ensure that the physical and mental demands of the work task are well within those respective capabilities of the worker (within a prescribed environment) (Ayoub, 1992). However, there are numerous factors involved in both the work task and the individual worker that could impact the balance of this system, as depicted by the illustration in Figure 4 (Dempsey, 1998).

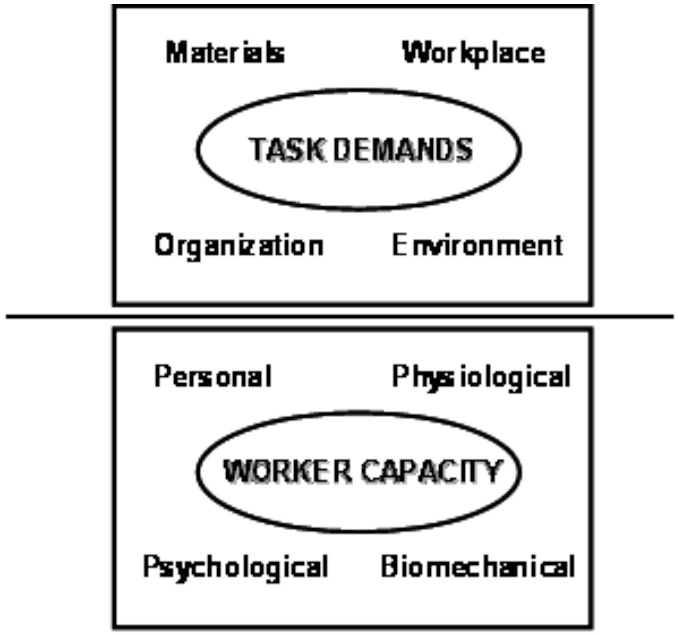


Figure 4: Illustration of factors that can influence the balance between the task and worker (adapted from Dempsey, 1998).

Methods generally applied to ensure a balance between the work task and the worker include implementing a work force selection process, providing education and training, and/or (re)designing jobs with respect to the work task or environment (Snook, 1987). Of those three, job (re)design is the most effective at ensuring the balance when worker capabilities are incorporated into the design. This incorporation is achieved through the application of job design limits and guidelines with respect to the predominant human capability being taxed as determined by the task's characteristics (e.g., frequency and duration of lifted load). These limits are designed to help prevent the demands of the task from exceeding what the worker is safely capable of handling, thus they are critical in minimizing MMH-related injuries.

The limits are reflective of the worker's physical response associated with one of the three MMH system components: worker, task, or environment. These limits are dependent upon the principled approach utilized, be it biomechanical, physiological, or psychophysical (Sanders and McCormick, 1993):

Biomechanical Approach in Assessing MMH

Utilized primarily for infrequent heavy lifting tasks, biomechanical MMH job design limits were developed to ensure the safe function of the worker's musculoskeletal system. As noted by Dempsey (1998), the two most commonly used criteria to develop design limits relate to the compression forces applied to the spinal joints (L4/L5 or L5/S1) or the maximum torque about the joints utilized in MMH tasks. In this approach, body segment parameters are evaluated and assessed with biomechanical principles to describe the various reactive forces and torques about those segments and in turn are used to develop design limits (Asmussen, Hansen, & Lammert, 1965; Garg & Ayoub, 1980; Poulsen & Jorgensen, 1971). Chaffin (1969) has done a considerable amount of research utilizing this approach, having developed static biomechanical models used in developing lifting limits. Model variations include the computerized human body model (Chaffin, 1969; Chaffin & Baker, 1970) and strength prediction models for MMH (Martin & Chaffin, 1972). Dynamic biomechanical models were later developed (El-Bassousi, 1974; Frievalds, Chaffin, Garg, & Lee, 1984) and were deemed more applicable to the dynamic nature of MMH and also because static models have a tendency to underestimate the stresses of dynamic activities (McGill & Norman, 1985).

Physiological Approach in Assessing MMH

In contrast with the biomechanical approach limits, physiological limits are designed to ensure that the work does not exceed the tolerance of the worker's cardiopulmonary system. More specifically, these limits relate to physical fatigue including whole-body fatigue and, to a lesser extent, local muscle fatigue. In the case of repetitive lifting, it is the physiological approach that becomes the most applicable given that the cardiopulmonary system becomes predominant in terms of maintaining homeostatic equilibrium with the environment (Asfour, 1980).

The research using this approach to evaluate the physiological responses to work including MMH activities is vast, with many studies and reviews resulting in numerous specific quantitative guidelines all addressing the control of fatigue. Commonly measured indices among these studies include energy expenditure, oxygen consumption (which can be easily converted into energy expenditure), and heart rate. Percentage of Maximum Voluntary Contraction (MVC) and electrical activity of the muscle via electromyography (EMG) are commonly used to calculate measures for local muscle fatigue.

In MMH research, evaluating the energy expenditure of an activity is the main objective, particularly for research relating to whole-body fatigue. Traditionally within these research studies, the energy expended with respect to the person's Maximum Aerobic Capacity (MAC) is usually the evaluated outcome, especially when work is to be assessed against design guidelines. For these studies, subjects are subjected to maximal exercise testing via treadmill or cycle ergometer to ascertain MAC of the individuals.

This is compared to measured energy expenditure of the work activity in question. Energy expenditure during a work activity can be obtained in a number of validated ways with the most common being the collection of oxygen consumption or heart rate. Because oxygen is utilized in the releasing of energy during aerobic metabolism, the amount of oxygen consumed during an activity can be easily and directly converted into energy expenditure. The physical means of collecting oxygen consumption can be accomplished by using indirect calorimeter methods (e.g., metabolic carts and portable Oxylog meters). However, these methods can be cumbersome and intrusive; possibly interfering with the work activity being evaluated. Heart rate, collected via telemetry, is often used as a surrogate for collecting oxygen consumption because it is less invasive and its linear relationship to oxygen consumption makes conversion to energy expenditure easy (Sanders and McCormick, 1993). While oxygen consumption and heart rate are staple physiological measures to ascertain energy expenditure and the overall load of the work, technology has most recently allowed for even less invasive means to obtain energy expenditure data while a person is performing work or exercise. Portable physical activity monitors, such as the Body Media SenseWear Armband, are small devices worn on the subjects' person and utilizes heat from skin contact to calculate energy expenditure. Although fairly new in research, they have been the subject of several validation studies (Galvani, Andreoletti, Besi, & Faina, 2007; Jakicic et al., 2004; King, Torres, Potter, Brooks, & Coleman, 2004; Wadsworth, Howard, Hallam, & Blunt, 2005) with respect to their ability to effectively estimate energy expenditure. Wadsworth et al. (2005) examined the effectiveness of the Body Media SenseWear Armband for measuring energy expenditure both at rest and at exercise and concluded that it was a valid method. Similarly, Jakicic et al.'s (2004) study found the device provided an accurate assessment of energy expenditure when appropriate algorithms were applied to the data. King et al. (2004) found that the SenseWear Armband provided the best energy expenditure estimate among other activity monitors when assessing energy expenditure while running at different speeds during treadmill exercise. See Feo & Loreto (2005) for further review of the monitors.

In measuring local muscle fatigue, both MVC and electromyography (EMG) activity are commonly used indices in MMH research. Although the use of MVC is often used as a measure of muscle fatigue, EMG analysis has proven to be more useful to ergonomists and physiologists that seek to understand the preceding events to failure for the development of mitigation solutions. Given the generally accepted concept that muscle fatigue is a progressive event, EMG analysis allows for the monitoring of this progression (De Luca, 1997). Percentage of MVC measures the decrease in the maximum voluntary contraction for a desired muscle over time. However, this measurement of force output is only measuring the end result of fatigue. In contrast, EMG activity identified from recorded signals can be used to assess the level and amount of muscle fatigue over time. Because it has been shown that there is a correlation between EMG activity and muscular force (Sanders & McCormick, 1993), EMG is a viable means of measuring one indicator of muscle fatigue. When muscles fatigue, there is a relative alteration of the EMG spectral activity and this spectral modification can be quantified by tracking an indicator of a desired frequency spectrum such as median frequency, or by calculating a ratio of a low-frequency to high-frequency bandwidths, or by integrating the area corresponding to the decrease of the median frequency (De Luca, 1997).

In terms of oxygen consumption work design limits, a number of values and ranges of values have been reported. Arguably the most cited guideline is a sustained maximum of 33% maximum aerobic capacity (MAC) for an eight hour day as reported by Garg, Hagglund, and Mericle (1986) and by which many work/rest cycle models are based upon (Muller, 1953; Murrell, 1965; Spitzer, 1952). In contrast, studies conducted by Astrand (1967) led to a suggestion of 40% VO_{2max}, and Jorgensen (1985) and Ayoub & Mital (1989) reported ranges of 30-35% and 25 -35% VO_{2max}, respectively. In a study evaluating high frequency manual material handling activities and differences between the genders, Mital, Nicholson, and Ayoub (1993) reported that for an 8-hour workday overexertion could be avoided if work was designed to keep energy expenditure rates at or below 29% and 28% maximal aerobic capacity for males and females, respectively.

Due to its widespread use, HR guidelines are readily available as well. These include a recommended upper limits of 90-130 beats per minute for continuous work (Ayoub & Mital, 1989), and a recommended limit of a 30-35 bpm ΔHR from resting HR to work HR (Grandjean, 1988). In terms of heart rate measures during recovery, Brouha (1960) recommended that the measured mean pulse rate recorded at 60 seconds after the cessation of work be 110 beats per minute (bpm) or less to ensure the work is at a safe stress level.

The early work of Rohmert (1960) and Rohmert (1973a), which identified recovery as a exponential function of the degree of fatigue, gave way to guidelines for localized muscle fatigue, although less likely used within MMH (Dempsey, 1998). Often used limits are Grandjean's (1988) levels of <8-15% MVC for static work and <30% MVC for dynamic work. Currently, there are no available design limits reflective of

EMG activity and studies utilizing this measure often normalize it amongst individual MVCs.

A great deal of research has been conducted in examining the physical response to the varying factors involved in MMH, such as load dimensions, weight, and coupling using the physiological approach. With respect to the MMH task characteristics recognized as contributing factors to the hazard of MMH (Ayoub & Mital, 1989), a sampling of notable studies evaluating the respective characteristic using this approach is included in Table 1 (adapted from Ayoub & Mital, 1989).

Table 1
Sampling of highly cited research studies evaluating the physiological responses to various select MMH work factors using either the physiological or psychophysical approach (adapted from Ayoub & Mital, 1989).

Study Characteristic	Researcher(s)	Physiological Approach	Psychophysical Approach
Frequency	Asfour (1980)	●	●
	Ayoub (1977)	●	●
	Ciriello & Snook (1983)		●
	Garg & Saxena (1979)	●	
	Garg & Saxena (1982)		●
	Mital (1984a; 1984b)	●	●
	Mital & Asfour (1983)	●	●
	Mital & Ayoub (1980)		●
	Snook (1978)		●
Task Duration	Garg and Saxena (1980)	●	
	Legg & Myles (1981)	●	●
	Karwowski & Yates		●
Object size	Frievalds, Chaffin, Garg, & Lee (1984)		●

	Garg and Saxena (1980)		●
	Mital (1984a; 1984b)	●	●
	Mital & Ayoub (1981)	●	
Couplings	Frievalds, Chaffin, Garg, & Lee (1984)		●
	Garg & Saxena (1980)		●
	Mital & Ayoub (1981)	●	
Object Weight/Exertion	Asfour (1980)	●	●
	Frievalds, Chaffin, Garg, & Lee (1984)		●
	Garg & Saxena (1979)	●	●
	Garg & Saxena (1980)		●
	Mital & Ayoub (1981)	●	
	Mital & Fard (1986)	●	●
Vertical Lift Height	Ciriello & Snook (1983)		●
	Mital (1984a; 1984b)	●	●
	Snook (1978)		●
Distance Travelled/Slope and Traction	Ciriello & Snook (1983)		●
	Snook (1978)		●
	Yousef, Dill & Freeland	●	
Posture/Technique	Chaffin, Andres, & Garg		●
	Garg & Herrin (1979)	●	
	Garg & Saxena (1979)	●	●
	Kumar (1984)	●	

A number of researchers have developed prediction models for both whole-body and localized muscle fatigue with respect to MMH activities (Aberg, Elgstrand, Magnus,& Lindholm, 1969; Asfour, 1980; Choi, 2006; Frederik, 1959; Garg, Chaffin, &

Herrin, 1978). Garg et al. (1978) analytical model is arguably the most widely used model for the prediction of energy expenditure in MMH activities (sitting, standing, lifting lowering, carrying, pushing, pulling, and walking). Inputs, which include the subject's body weight and gender, the starting and ending heights of the lift, the distance of carry, the frequency of lift, and the weight lifted, are easy to ascertain and no initial oxygen consumption testing is required to compute energy expenditure. Within this model, regression equations for various activities are used to the estimate the energy expenditure rate for a task. As an example, a 'Stoop Lift' (from a standing position) is as follows (Ayoub & Mital, 1989):

$$E = 0.024BW + (0.0325BW (0.81\text{-}H_1) + (31.41L + 0.76SL) \text{ x } (H_2\text{-}H_1) \text{ x } F/100$$

for $H_1 < H_2 \leq 0.81$

where:

E = energy expenditure (kcal/min)

BW = body weight (kg)

H_1 = starting point of lift (m)

H_2 = ending point of lift (m)

S = gender (male is 1; female is 2)

F = frequency of lift (lifts/min)

L = weight lifted (kg)

Also with this model, there is an assumption that a task can be divided into a series of subtasks or activities and that the total energy expenditure for the complete task is a summation of the rates developed for the separate parts (Garg et al., 1978) as depicted by the following model:

$$\overline{\dot{E}_{job}} = \left(\sum_{i=1}^{n_i} \dot{E}_{pos} \times t_1 + \sum_{i=1}^{n} \Delta\dot{E}_{taski}\right) /$$

where:

$\overline{\dot{E}_{job}}$ = Average energy expenditure rate of the job (kcal/min)

$\dot{E}_{pos}$= Metabolic energy expenditure rate due to maintenance of i^{th} posture (kcal/min)

t_i = Time duration of i^{th} posture (min)

n_i = Total number of body postures employed in the job

$\Delta\dot{E}_{taski}$ = Net metabolic energy expenditure of the i^{th} task in steady state posture (kcal)

n = Total number of tasks given in the job

T = Time duration of the job

Psychophysical Approach in Assessing MMH

Within this approach, which combines elements of both biomechanical and physiological principles, limits are designed to ensure work is within a worker's acceptable range of perceived stress as determined by the individual's perception of exertion. This concept is reliant on sensory function and perception work conducted by Stevens (1960) which asserted that the strength of sensation is in relation to the intensity of its physical stimulus by means of the following power function:

$$\Psi = k\,\Phi^{n}$$

where:

Ψ = strength of the sensation

Φ = intensity of the physical stimulus

k = constant which is a function of the particular units used, and

n = slope of the line that represents the power function when plotted in log-log coordinates (1.6 for the perception of muscular effort; 1.45 for lifting weights)

Snook (1978) utilized the principles of psychophysics to determine subjective limits of work. In ascertaining the Maximum Acceptable Weight Limit (MAWL), a commonly used psychophysical measure in MMH, his series of studies centered on determining human capabilities by evaluating the perceived strain of an activity. The study protocol, which became the gold standard in determining MAWL for other MMH activities, included instructing subjects to adjust workloads by adding or removing weight from a box until reaching maximum weight levels that they 'believed' could be personally handled (lift and lower) for an eight hour day without undue strain or discomfort.

Psychophysical criteria for aiding in work (re)design are abundant, specifically for MMH lifting and lowering tasks (Snook & Irvine, 1967; Snook, Irvine, & Bass, 1970; Snook & Ciriello, 1974; Snook & Ciriello, 1991) upon which numerous MAWL tables have been developed. As with the physiological approach, the psychophysical approach has been thoroughly used to examine the human response to varying MMH tasks. Aghazadeh & Ayoub (1985), Ayoub, Dryden, McDaniel, Knipfer, & Aghazadeh (1976), Dryden (1973), and McDaniel (1972) looked at the effect work task variables (i.e., lifting frequency, height of lift, load dimensions) as well as worker variables (i.e., body weight, leg, back, and arm strength, and static endurance) had on psychophysical aspects of handling loads during MMH activities. Additional sampling of highly cited MMH studies using the psychophysical approach is included in Table 1.

Although not used for criteria development, the Borg-RPE Scale developed by Borg (1985) is a repeatedly collected psychophysical measure. The RPE scale is a series of numerical ratings designed to quantify a person's individualized sensitivity to the amount of effort required to perform physical tasks. Specifically, Borg's RPE scale ranging from 6 to 20 (Figure 5) is a scale used to rate exertion during dynamic work (Borg, 1998). It has been found effective in assessing physical exertion because of its high correlation in changes in heart rate and oxygen consumption. Due to its ease of use, it is often used to collect subjective measures of fatigue, including both whole-body and localized muscle fatigue, in MMH activities (see Asfour, Ayoub, Mital, & Bethea, 1983; Capodaglio, Capodaglio, & Bazzini, 1996; Dehlin & Jaderberg, 1982; Hagen, Harms-Ringdahl, & Hallen, 1994).

6	**No exertion at all**
7	
	Extremely light
8	
9	**Very light**
10	
11	**Light**
12	
13	**Somewhat hard**
14	
15	**Hard (heavy)**
16	
17	**Very hard**
18	
19	**Extremely hard**
20	**Maximal exertion**

Figure 5: Borg's RPE Scale (Borg, 1998)

Fatigue

The circumstances surrounding the MMH task, such as its frequency or duration, often determines the appropriate approach to use and thus the respective limit or limits to apply. Considering the repetitive lifting nature of many MMH specific jobs, the physiological and psychophysical approaches are often utilized to determine limits and to conduct related research. Despite the variety in the physiological and psychophysical criteria and targeted measures, all relate to the development of fatigue as result of the work conducted. The reduction of fatigue or the prevention of excessive fatigue during work has been a significant goal when designing processes and work practices to maintain or increase productivity and ensure worker health and safety (Konz & Johnson, 2000).

By its definition, fatigue is the decreased effort to do work (Grandjean, 1988), referencing either a physiological, psychological, or mechanical 'effort' (Kumar, 1994). Fatigue is categorized as either (Konz & Johnson, 2000):

- General Whole Body Fatigue: cardiovascular system / physiological
- Localized Muscular Fatigue: muscles / physiological
- Mental Fatigue: brain / physiological and psychological

Whole Body Fatigue

Generally speaking, whole-body fatigue is the depletion of physiological energy (as it relates to the function of the entire body) to a low reserve level due to either prolonged submaximal activity or a short (but sufficient) period of high intensity activity (Kumar, 1994). Because most MMH work is classified as submaximal activities but carried out for extended periods of time, this type of fatigue has been the major focus in most MMH research.

Localized Muscle Fatigue

In contrast to whole-body fatigue, local muscle fatigue relates to the loss in energy in specific muscle groups. It is accepted that muscle fatigue is a cumulative process in which there is a gradual loss in the muscle capabilities despite continued neural stimulation (Martini, 1998). The mechanism for the loss of muscle strength is still unclear but many researchers have offered a number of reasons including neuromuscular fatigue visible in EMG (De Luca, 1997), the interference in the regulation of intracellular Ca^{2+} concentrations due to damage to the sarcoplasmic reticulum (Martini, 1998), blood occlusion from intramuscular pressure leading to lactic acidosis (Astrand and Rodahl, 1970; Grandjean, 1998), acetylcholine depletion (Astrand and Rodahl, 1970), or potassium ion depletion (Sjogaard, 1986; Bogdanis, Nevill, Lakomy, Graham, & Louis, 1996). While the debate in terms of the exact mechanism or combination of mechanisms responsible for muscle fatigue continues, the general view is that muscle fatigue is cumulative. As noted by Iridiastadi (2003), because fatigue is a progressive event, it can be indicated by a number of time-dependent changes in which valuable information can be obtained by examining this process throughout.

Traditionally a focus of occupations in which static loading is prevalent, local muscle fatigue has more recently been a focus of MMH studies which has both static and dynamic elements. Choi (2006) recently investigated the link between local muscle fatigue and common MMH tasks involved in parcel sorting and Shin and Kim (2007) measured the impact different recovery durations have on trunk muscle fatigue during dynamic lifting.

Mental Fatigue

Mental fatigue relates to the decrease in the "will" to perform work. This can be manifested in a number of ways including the lack of concentration, marked sleepiness or tiredness, or an increase in human error. Although mental fatigue is often studied to determine its impact on productivity in the sense of quantity and quality of output, there have been studies conducted to examine the impact is has on the physiological system. It has been shown that certain levels of mental workload can increase respiratory rates and heart rates (Konz, 1988a). In terms of motivation, studies conducted by Asmussen & Mazin (1978a, & 1978b) showed that mental diversions such as increasing concentration by doing mental arithmetic increased work output when done so between fatiguing bouts of exercise.

Despite the simple generalizations of fatigue and the accepted means of measures, it is still extremely difficult to fully understand and evaluate given its complexity in terms of its varied responses. With mental fatigue, the lack of effort could be expressed as a lack of motivation or an inability to effectively or efficiently complete simple mental tasks. Whole body and local muscle fatigue may be expressed as the reduced ability to exert physical force and/or physical discomfort. Given the characteristics of the task, fatigue could be influenced and exhibited as a symptom of all three categories – and to any degree of each (Astrand & Rodahl, 1970, Basmajian & De Luca, 1985). Furthermore, research has shown that fatigue is relative to individual factors such as physical conditioning (Ayoub & Mital, 1989; Genaidy, Davis, Delgado, Garcia, & Al-Herzalla, 1994; Genaidy, Gupta, & Al Shedi, 1990; Genaidy, Karwowksi, Guo, Hildalgo, & Garbutt, 1992) and gender (Albert, Wrigley, McLean, & Sleibert, 2006; Hicks, Kent-Braun, & Ditor, 2001; and Russ & Kent-Braun, 2003). It is also relative to environmental factors such as temperature and humidity levels (Febbraio et al., 1994; Gonzalez-Alonso, Grandall, & Johnson, 2008; Kay et al., 2001; Neilsen, Savard, Richter, Hardgreaves, & Saltin, 1990). These individual and environmental factors and the combination thereof only add to the difficulty in effectively and efficiently assessing fatigue; especially when considering the physiological complexity of the neuromuscular system. This is evident in the research community's inability to determine an absolute physiological basis for fatigue.

Fatigue and Musculoskeletal Disorders and Injuries

The precise mechanism for the development of MSDs is still unclear but several work factors have been accepted as increasing the risk of its occurrence. These factors include posture, force, repetition, vibration, and a combination thereof (National Institute of Occupational Safety and Health [NIOSH], 1997). In addition to these physical factors, a number of studies have been conducted in order to evaluate the solitary and interactive effects of psychosocial factors (e.g., job control) in the development and abatement of MSDs as well (Fagarasanu & Kumar 2003; Menzel, 2007; Rietveld, van Beest, & Kamphuis, 2007; Russo, Murphy, Lessoway, & Berkowitz, 2002; Smith, Mihashi, Koga, Adachi, & Ishitake, 2006).

Although not traditionally labeled 'risk factor' for MSD, fatigue control is a common goal for work design with worker's comfort, safety, and productivity as a goal (Konz & Johnson, 2000). Research interest in fatigue is not a recent occurrence. Research involving fatigue in the early years was conducted in the Scientific Management and motion economy work conducted by Taylor (1913) and Gilbreth & Gilbreth (1916). However, these studies only related fatigue to the reduction in performance. Later research (Mital, 1984a; Snook & Ciriello, 1974; Snook & Ciriello, 1991; Snook & Irvine, 1967; Snook et al. 1970) resulted in design guidelines that reference the worker's comfort, or perception of, in conjunction with productivity capabilities. Whereas fatigue has long since been attributed to a hindrance to productivity and worker discomfort, fatigue examined as a risk factor for the increased susceptibility of both acute and chronic injuries has been a major focus of research as of late, particularly with regards to localized muscle fatigue. In terms of the proposed reasoning, a number of studies have identified various characteristics of fatigued muscles that may attribute to the causation of injuries. It has been shown that as muscles fatigue, their ability to absorb energy in terms of shock and stress decreases (Lepers, Hausswirth, Maffiuletti, Brisswalter, & van Hoecke, 2000; Mair, 1996; Wojtys, Wylie, & Huston, 1996) as well as their ability to stabilize joints (Chappell et al., 2005; Sparto & Parniapour, 1998). In a study examining the impact fatigue has on knee kinetics, Chappell et al. (2005) determined that in addition to a decrease in stabilization about the knee joint during jumping tasks, the fatigued knee muscles altered motor control strategies and therefore led to an increase in the risk of injury. Pedersen, Lonn, Hellstrom, Djupsjobacka, & Johansson (1999) determined that localized fatigue of the shoulder muscle reduces the acuity of movement sense and that there was a lower probability of distinguishing between different movement velocities thus increasing the chances of injury to the shoulder. Fatigue in one muscle group has also been found to increase the risk of injury to a separate muscle group or other musculoskeletal structure. Chen (1999) found that after continuous lifting, subjects altered the acceleration within their lifting strategies due to arm fatigue which in turn increased the compressive forces at the L5/S1 in the spinal column. The idea that fatigue plays a direct role in the development of musculoskeletal injuries was further evident in an epidemiological study designed to determine risk factors for shoulder and elbow injuries among baseball pitchers conducted by Olsen, Fleisig, Dun, Loftice, & Andrews (2006). Within this study, which compared the pitchers with and without a history of shoulder and elbow injuries, it was determined that fatigue had a strong association with the development of such injuries.

It has been stated that whole body fatigue is less likely to have a direct effect on the development of musculoskeletal disorders; however it can lead to a decrease in psychomotor skills and a reduction in comfort (Chengalur, Rodgers, & Bernard, 2004). Furthermore, the mechanisms involved in the development of whole body fatigue indirectly impact those involved in localized muscle fatigue. In order for muscles to perform work, energy in the form of the biological releasing and gaining of adenosine phosphate (ATP) or creatine phosphate compounds is required. This energy is provided by way of either the aerobic oxidative phosphorylation or one of the two anaerobic processes, glycolysis or the phosphagen system. Within the aerobic process, oxygen serves as the final acceptor in the chemical process and is available to be delivered to the muscle cells at a sufficient pace with respiration and circulation adapting to the work. In contrast, with the anaerobic process oxygen is not available for delivery to the muscle cells. Instead, energy is supplied through the breakdown glucose into pyruvic acid or lactic acid in glycolysis or the breakdown of phosphocreatine in the phosphagen system. Both of these anaerobic processes yield high energy ATP, but in very small amounts; thus these processes are not utilized long term. When transitioning to work/exercise from rest, oxygen uptake increases mono-exponentially until steady state. This results in a lag in the oxygen uptake otherwise known as an oxygen deficit. Because of this lack of sufficient oxygen supply at the onset of work/exercise, the anaerobic processes will provide the necessary energy in the beginning until a sufficient supply of oxygen is available and the aerobic process can take over. This exchange in process dominance can be delayed if the work does not allow for the accumulation of needed oxygen (Astrand & Rodahl, 1970; Harris, Adams, & Keith, 2006; Powers & Howley, 2007). During work that requires force production, as is the case with lifting, carrying, and lowering loads activities of material handling, muscles can fatigue faster due to the reliance of the inherently short duration of anaerobic metabolism. Therefore, to minimize fatiguing of the muscles and consequently the decrease in the muscles' ability to stabilize joints and absorb energy from shock and stress, a sufficient supply of oxygen is needed. Thus, controlling the dominating metabolic process involved in the required work is an advantageous step in controlling the development of local muscle fatigue. Furthermore, it has been theorized that muscle fatigue rates are minimized when the O_2 deficit of the muscle is reduced by faster oxygen uptake kinetics (Burnley and Jones, 2007), thus controlling these responses could have an impact on the development of muscle related injuries as well.

Minimizing Fatigue

Given fatigue's well documented negative impact on productivity and its potential as a direct risk factor in the development of both acute and cumulative injuries, the prevention or minimization of fatigue is a common goal in MMH. It is a well known accepted fact that fatigue can be remedied by adequate recovery. As the understanding of the development of fatigue is important to the design of safe and efficient MMH systems, the understanding of recovery from fatigue is just as important. The value recovery, or the rest break, is a function of (Konz & Johnson, 2000):

- how fatigued the cardiovascular system, muscle, or brain is when recovery is started
- the length of the recovery, and
- what happens to the cardiovascular system, muscle, or brain during recovery

There are many methods recommended and employed in industry to prevent excessive fatigue or ensure adequate recovery from fatiguing activities, be it whole-body, localized, or mental. Utilizing recommended limits to (re)design work such that work intensities are low enough so that the worker's capabilities are sufficiently met and fatigue is avoided is ideal. However, there are times, especially in MMH activities, where this is not feasible and recovery needs to be scheduled into the work. Allowing for adequate recovery time after any amount of physical exertion, or work, is necessary to prevent the development of fatigue to adverse levels to ensure continued optimal performance and safety. This approach is evident in industries with the implementation of general rest breaks in their work policies, contracts, and work measurement standards.

With work measurement standards, the standards dictate the productivity outcome that is to be expected of the worker and as such can often dictate their pace if they are to be held to that standard. In developing standards, a percentage of time, or allowance, is given in addition to the normal time it takes to complete a task. This allowance takes into account the extra time needed for the worker's handling of personal needs, any expected fatigue the worker will incur as a result of the work task, and any expected delay outside the control of the worker. Of the three, the fatigue allowance is often the most misunderstood and ineffectively applied allowance because there is no real consensus on how to calculate or how to apply effectively. There is no shortage on the methods employed by engineers to determine these allowances as tools/worksheets are abundant. These tools/worksheets can differ drastically in their calculation of fatigue and which factors impacting fatigue are included. This was evident is a study conducted by Lund & Mericle (2000) in which industrial engineers used four widely used, albeit dated, standardized job analyzes (Cornman, 1970; International Labour Office [ILO], 1979; Page, 1964; Williams, 1973) to develop a work standard for one job. The results showed that inter-rater reliability and cross-validation were very low, despite extensive experience and adequate training provided to the engineers. Whereas the effective use of these analyzes to develop reliable fatigue allowances is an issue, more concerning were the varying and conflicting methods used within each analysis tool to determine fatigue. Although the general idea for fatigue allowance worksheets is to provide and sum individualized 'fatigue values' for work and environmental factors that may impact the expected degree of fatigue, the methods employed and the provided values differ significantly amongst the tools; particularly for the before mentioned tools evaluated in the Lund & Mericle (2000) study. As noted by the authors, the tools varied in the level of detail offered in defining and describing the factors industrial engineers must decide upon when developing the allowance. It is this lack of clarity that aided in the inconsistency of fatigue allowance development amongst the subjects in the study. More concerning is the lack of empirical evidence or validation of the ‘fatigue values’ supplied by the tools. Therefore, it was the recommendation of the authors that fatigue allowances included in standard job analyzes (particularly the four tools that were part of their study) be validated against objective physiological measures such as those reviewed earlier. Unfortunately, no recent changes in the methods to develop fatigue allowances for work measurement, particularly warehouse operations, could be found during this literature review.

Without a consensus on the appropriate amount of allowance to provide, work designed to meet developed standards may put workers at risk of excessive fatigue, as was found by a study on warehouse operators conducted by Garg, Hagglund, & Mericle (1986). In this study, the physiological responses (oxygen uptake and heart rates) of sixty-three male grocery warehouse workers from three different warehouses were monitored throughout their order selecting tasks and their work measurement determined performance levels were compared to company time standards. In these standards, job ratings for stop watch studies were subjective, and fatigue allowances were based on arbitrary values or not included as was the case for one warehouse. It should be noted the participating warehouses also implemented various disciplinary actions with respect to failure to meet their performance standards. The results of the study showed that 40% of the workers failed to meet the 100% time performance level. It was also determined that the mean metabolic rate for all the workers exceeded the 5kcal/min guideline (6.7kcal/min) that would constitute the inclusion of a fatigue allowance, but the authors of the study noted that fatigue allowances provided by the warehouses were inadequate.

This was further indicated in a study conducted by Garg and Saxena (1985) where they determined that traditional work measurement techniques were physiologically insufficient for warehouse operations, especially for female workers, due to the stresses involved with lifting.

Work/rest schedules is another widely used method to minimize fatigue. By altering the characteristics of work/rest intervals, such as intensity and duration, changes in the metabolic pathways within muscle cells, as well as oxygen delivery to muscles, can be seen (Laursen & Jenkins, 2002). Incorporating a recovery break prior to reaching excessive levels is key to minimizing fatigue. However, determining the most advantageous recovery duration, type, and placement in the work/rest scheme has proven to be difficult due to the extensive amount of variables associated with the development of fatigue and with the characteristics of the recovery as well. The duration of the recovery is a highly researched issue. Whereas fatigue increase exponentially, recovery from fatigue is exponential as well (Konz, 1998b) with a majority of the recovery occurring within the first part of the break. Since recovery is a function of the degree of fatigue at the start of the break, a longer work period would require a longer recovery. Therefore there is the common recommendation that frequent short breaks should be allowed as opposed to infrequent long breaks. Methods used to determine the appropriate amount of recovery necessary vary. Two recommended basis for the methods, as noted in Ayoub & Mital (1989) include the 1) strain based and 2) the metabolic energy expenditure based methods. With strain based models, rest allowances (as proposed by Rohmert (1973b)) are determined based on working heart rate levels above resting. With the metabolic energy expenditure based method, allowances are calculated per various models (Muller, 1953; Murrell, 1965; Spitzer, 1952) with the 33% of aerobic capacity guideline used as the basis. Despite the models and current understanding of recovery duration, developing effective work/rest schedules is still a common concern in industry.

The type of recovery, whether passive or active, has been shown to be an important factor to the effectiveness of a work/rest scheme as well. Passive recovery refers to when there is no physical activity occurring during rest whereas active recovery includes varying degrees of activity, and each can impact the time to recovery from fatigue as well as the development of it. Studies evaluating the effects of active recovery have shown it to be better in terms of increased productivity (Swanson & Sauter, 1993; Thompson, 1991), decrease in lost time injury (Thompson, 1991), decrease in muscle fatigue due to increased blood circulation (Bishop, Ruch, & Paun, 2007; Konz & Johnson, 2000) and faster lactate removal (Bond, Adams, Tearney, Gresham, & Ruff, 1991; Taoutaou et al., 1996; Thiriet et al., 1993) as compared to passive recovery. Active recovery has also been shown to increase power output for subsequent high intensity exercises (Signorile, Tremblay, & Ingalls, 1993; Bogdanis, Nevill, Lakomy, Graham, & Louis, 1996; Connolly, Brennan, & Lauson,, 2003). Thiriet's (1993) study on consecutive maximum level exercises showed that passive recovery, or doing nothing while at rest from repeated maximal exercise, exhibited a decrease in performance. In contrast, some studies have shown that there is no significant difference due to the type of recovery in terms of fatigue rate (Bond et al., 1991; Signorile, 1993) or performance (Toubekis, Douda, & Tokmakidis, 2005; Toubekis, Peyrebrune, Lakomy, & Nevill, 2008). The duration and intensity of the active rest can have a significant impact on its effectiveness. Toubekis et al. (2005) and Toubekis et al. (2008) examined the duration of active recovery in highly fatiguing repeated swimming exercises. By evaluating the performance, it was determined that active recovery at 60% of maximal swimming effort either had a beneficial or detrimental effect as dependent on recovery duration (<2min recovery resulted in decreased performance). In evaluating the effect of different active recovery intensities, Toubekis, Smilios, Bogdanis, Mavridis, & Tokmakidis (2006) determined that active recoveries set at 50% and 60% of maximum 25-meter swimming pace decreased performance in swimmers, Bogdanis et al. (1996) found that an active recovery of 40% VO_{2max} increased power output in cyclists, and Bond et al. (1991) found that there was no effect in cycling performance when active recovery was 30% VO_{2max}. Although there are well expected benefits to incorporating the most appropriate recovery type at the most effective duration into a work/rest scheme, the conflicting results of the previous studies illuminate the complications that are inherent when trying to determine that optimal scheme.

Despite the complications, the concept of optimizing the work/rest scheme for endurance training purposes is nothing new. Endurance athletes, such as marathon runners, have experimented with alternative training techniques to enhance performance for a number of years. These techniques particularly focus on alternating periods of active recovery of varying levels of intensity and duration in order to minimize fatigue (whole-body and, consequently, local muscle fatigue). One such technique is Fartlek (or speed play) which was developed by Swedish runner Gosta Olander in the 1930's. Fartlek incorporates varying elements of endurance, rhythm, and speed in a continuous running nature where the runner alternates between intensities as determined by what they feel they are capable of doing at the time; making Fartlek a highly individualized training method. This non-systematic approach has been both criticized and praised because of its reliance on the runners' own characteristics (Graça, 2005). Despite the criticism, the Fartlek concept has been an effective training tool as evident by success stories such as Gunder Hagg's and Arne Anderson's numerous world records between 1942 to 1945. Another training method is interval training developed by Waldemar Gerschler and physiologist Herber Reindell in the 1950's. Interval training is a mix between Fartlek's alternation between fast and slow elements and Gerschler's earlier work on repetitions. With interval training, well defined running repetitions are separated by 'active intervals' for a maximum number of reps. This training method was widely accepted in the sports world after its introduction and adaptations of the technique are still used today for running, swimming, cycling and other cardio sports and activities (Graça, 2005).

Combined Manual Material Handling

The physiological cost of various MMH activities has nevertheless been extensively evaluated as evident from the before mentioned contribution of design guidelines utilizing the various approaches. For the most part, this research has centered on the physical cost of a single MMH activity, such as lifting or lowering. Determining the physiological cost for Combined Manual Material Handling (CMMH), which involves the combination of two of more MMH activities at a given time, has been less of a focus despite its high prevalence in industry (Jiang et al., 1986). The combination of activities implores the utilization of a variety of muscle groups at varying degrees as dependent on the activities. Despite this added complexity, it is still the practice to assess these activities by characterizing the entire job by its most significant individual task or by using the additive assumption that is the basis of the Garg et al. (1978) metabolic prediction model discussed earlier. However, this assumption has been shown not to be applicable for CMMH activities (Asfour, 1980; Taboun & Dutta 1989; and Straker, Stevenson, & Twomey, 1997, Straker, Stevenson, Twomey, & Smith, 1997) and that the assumption may even underestimate the physiological cost of CMMH work (Straker, Stevenson, & Twomey, 1996). This owns to the assertion made by Jiang, Smith, & Ayoub (1986) that CMMH is more stressful at certain handling frequencies than performing single activities. In examining the MAWL for CMMH, Iridiastadi & Aghazadeh (2005) found that CMMH-MAWLs were significantly lower than MAWLs previously published developed using a single activity (Mital, Founooni-Fard, & Brown, 1994). Their rationale was that the combination of activities did not provide adequate recovery between the activities, particularly when considering that activities in their study incorporated a considerable amount of static loading such as turning with a load which has been seen to easily lead to fatigue, as noted by Chaffin & Anderson (1991). It was the overall recommendation of the authors, as evident from their study and others investigating CMMH, that more research is needed in this area because of the conflicting results CMMH has in comparison to the traditional single MMH activity focused research.

Summary of Literature Review

As evident from this literature review, much research has been conducted in understanding the human response to various types of work, including MMH, and the numerous task characteristics inherent within them. This understanding has led to widely accepted design guidelines and recommendations in order to ensure a proper balance between the workers' capabilities (as examined via the research) and the demands of the work task. It is also evident that not all work situations and conditions, particularly those that are often prevalent in industry such as CMMH and dynamic work intensity changes, have been sufficiently examined. These situations offer up the possibility of significantly different physiological attributes and responses that could in turn make established recommendations as well as assessment tools derived from previous research inapplicable. Although the literature contains huge amounts of information as it relates to the effects of recovery type and duration as factors in work/rest schemes used for fatigue mitigation, that research reflects primarily on the whole-body fatigue impact, and more specifically during high intensity exercise/work. Therefore more research is needed to determine if the before mentioned effects of recovery type and duration apply similarly to the often times low to moderate level intensity of MMH work as well as on localized muscle fatigue. Furthermore, given the benefits seen with training techniques incorporating varying schemes of recovery type and duration, research is needed to determine if work sequencing that may mimic these schemes can be optimized, specifically for MMH.

The lack of research in these areas needs to be addressed in order to ensure that system balance is effectively achieved when applied in industries that require these working conditions. Thus it is the intent of this body of research to add to the established fatigue research in MMH by examining the physiological and psychophysical fatigue responses to combined manual material handling work that requires work intensity changes. It is the goal of this research that increased understanding of fatigue development within these work conditions will facilitate discussions as to the applicability of already established research and their derived guidelines and tools. Furthermore, additional understanding of the time-dependent physical responses of these situations could lead to enhancements in optimizing fatigue development mitigation techniques through systemization of variable workloads by way of human task-sequencing scheduling theory. As a result, this research could have the added benefit of bridging the interaction gap between ergonomics/human factors and operations research.

CHAPTER THREE

THE EFFECT OF VARYING SEQUENCE ORDER OF BOX WEIGHTS ON PHYSIOLOGICAL RESPONSES IN LOW INTENSITY COMBINED MANUAL MATERAL HANDLING TASK

Abstract

Although variation in work tasks and workloads are common in order picking manual material handling activities due to the wide variety of products pickers must handle, little is known about the changes in physiological responses used to infer whole-body fatigue these varying activities may evoke. Thus, it is not clear if optimizing order picking through selective work ordering is a viable means to control whole-body fatigue. The purpose of this study was to examine mean and peak steady state heart rate reserve (%HRR), heart rate time constant (τ), and work pulse (ΔHR) in simulated order picking work with varying baseline workloads. A secondary objective was to examine the mean and peak steady state heart rate reserve and rated perceived exertion (RPE) for order picking scenarios in varying sequence orders. Twenty-three subjects performed picking tasks where three work rates (2.3 kg (5 lb), 6.8 kg (15 lb), and 11.4 kg (25 lb) at 10/min) were picked until steady state after (1) a five minute standing rest, or after picking a (2) 'very low' intensity workload (5 lb), (3) 'low' intensity workload (15 lb), or (4) 'moderate' intensity workload (25 lb). Subjects also picked two extended sequences:

increasing, INC (5 lb → 15 lb → 25 lb) and mixed, MIX (5 lb → 25 lb → 15 lb). No significant differences were found between the baseline workloads for any heart rate responses ($p > 0.05$). Nor were there any significant differences between the sequence orders for the heart rate responses or RPE ($p > 0.05$). Results of the study suggest that selective work ordering would be ineffective in controlling whole-body fatigue, however, the noted limitations of the study support further research in the area.

Introduction

Improving the overall safety and efficiency of manual material handling (MMH) systems has been the focus of past and current MMH research. This research has led to the development of MMH work design limits and other recommendations to control excessive fatigue (Astrand, 1967; Ayoub & Mital, 1989; Grandjean, 1988; Jorgensen, 1985; Mital & Asfour, 1983); all in an effort to minimize injuries and improve productivity within the industry. However, recent injury data provided by the U.S. Bureau of Labor Statistics [BLS] indicate that injuries are still a significant concern within the MMH industry, particularly musculoskeletal disorders (MSDs) due to the inherent physical activities involved. According to the BLS (2009c), ‘laborers and freight, stock, and material movers’ had 27,040 reported MSDs in 2007; which equated to an incident rate of 149 per 10,000 full-time workers. Although this is slight decrease from the MSD incident rate reported for this occupation in 2006 (158), ‘laborers and freight, stock, and material movers’ has reported a significant percentage of total MSDs over the past number of years (Figure 6). This would suggest that more injury related research is still needed in this industry.

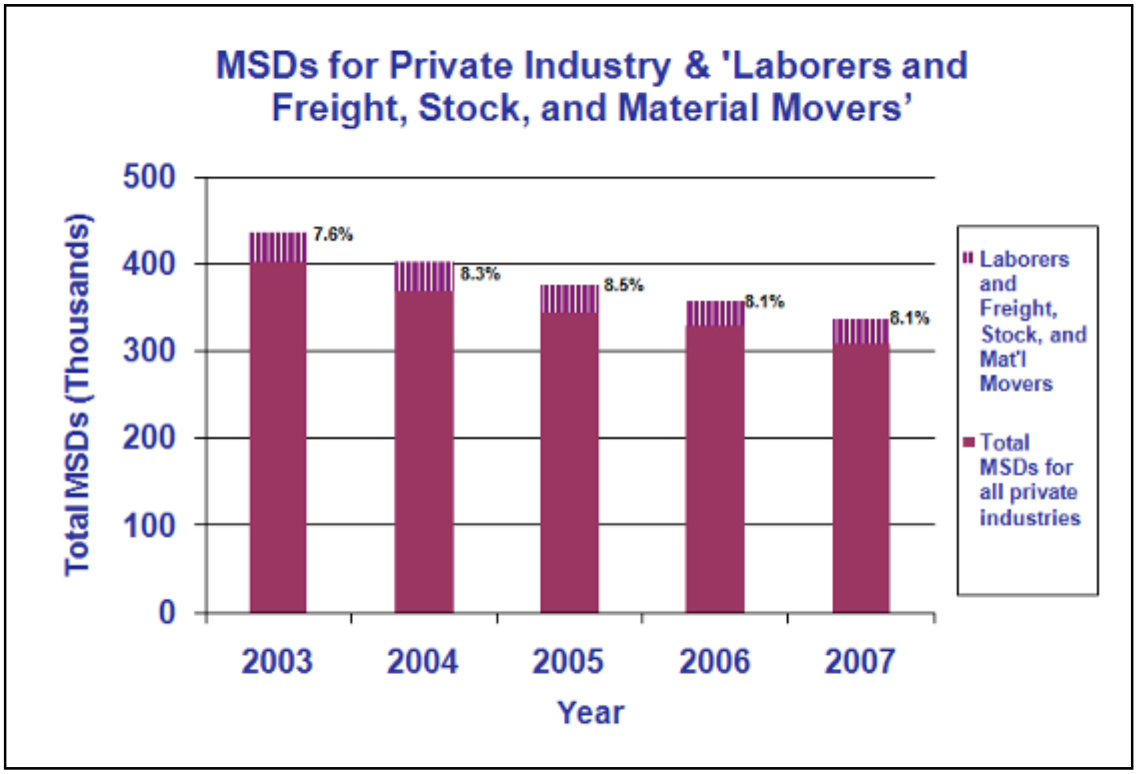


Figure 6: Reported MSDs for 'Laborers and Freight, Stock, and Material Movers' Occupation by Year (2003-2007). (BLS, 2009)

There is an abundance of research evaluating the development of fatigue in MMH due to varying factors such as frequency, load characteristics, or task duration (see Ayoub & Mital, 1989 for a review). However, research in general as it relates to the effect varying work intensity has on fatigue and recovery is extremely limited, and unfortunately non-existent in MMH research. Variations in work intensity are common in a number of MMH occupations, as seen in parcel loading and unloading occupations where the packages handled can vary significantly. A more specific example is warehouse distribution order picking where layout and order complexity requires manual picking. This is the case for the Big Lots Distribution Center of Montgomery, AL where order pickers within this center pick cases of products from pallets and place them on an outbound conveyor based on an assignment determined by customer (store) stocking needs. Since the stores carry and sell a huge variety of products, from small food items to bulky dog food, these cases can vary a great deal in size and weight.

In this situation, pickers are often exposed to drastic variations in work intensities as they complete order assignments. Determining the optimal sequencing of these orders with the objective of minimizing fatigue is a beneficial goal. By altering the characteristics of work/rest intervals as well intensity and duration, changes in the metabolic pathways within muscle cells, as well as oxygen delivery to muscles, can be seen (Laursen & Jenkins, 2002). By determining if re-ordering the work order as seen in these working conditions have an impact on the development patterns of whole-body fatigue, then optimizing the manipulation of these work intensities could possibly be an effective method to control this fatigue.

Optimizing work, or exercise intensities, for the purpose of endurance training has long been a goal for elite athletes. Recognizing the possibility that the added complexity of varying intensity could significantly impact the endurance of cyclists, Bjorklund, Petterson, & Schagatay (2007) observed the heart rate, lactate, potassium, and respiratory exchange ratio changes when workloads were varied in prolonged exercise. They concluded that variable intensity does impact lactate concentration when compared to incremental testing. A great deal of trial and error and targeted research has gone into developing effective training regimens using knowledge about human physiological responses to fatigue development and recovery and the impact altering these can have on performance. Examples of such training techniques are Fartlek and interval training. With Fartlek, high and low work intensities are altered non-systematically by the individual based on the person's real time perception of capabilities. Although criticized for its lack of structure, it has proven highly effective as a means for minimizing fatigue and increasing endurance. Interval training utilizes the Fartlek's use of low work intensities as recovery and strategically integrates them into structured repetitions (Graca, 2005) and has been shown to be highly effective, with variations of the techniques used for various endurance sports and activities. However, most of the focus of these fatigue and recovery effects has been for high to very high intensity exercise/work, and none specifically address MMH. It is still unclear if the same physiological impact strategically structuring intensities and active recoveries can be seen with low to moderate intensity, long duration, work common to MMH such as order picking.

Recent efforts have been made in the field of Operations Research to incorporate human characteristics such as fatigue in scheduling theory to mathematically optimize the safety and efficiency of work. Human task-sequencing, where tasks presented to the operator must be completed such that performance criteria are optimized, is one scheduling problem where ergonomic constraints can be incorporated into the scheduling of tasks such as those seen in the order picking scenario aforementioned (Lodree, Geiger, & Jiang, 2009). However, the available MMH research does not lend itself to solving this scheduling problem. MMH job design limits are useful as bounds for whole-body fatigue criteria, but assessing and comparing potential optimal solutions (sequences) per the scheduling problem is not possible with available research, prediction models and tools. Because there is a lack of MMH research as it relates to the fatigue response to varying work intensities, there is no clear understanding of the benefits, or detriments, varying these intensities can have on the development (rate and level) of fatigue.

Adding to the complexity of effectively assessing and addressing MMH jobs are the physical combination of MMH activities conducted in series and in conjunction with each other. The traditional method of assessing the metabolic cost of MMH activities is to separate the job into subtasks and assess each individually. Total energy cost of the job is determined by applying an additive assumption (Garg, Chaffin, & Herrin, 1978) which assumes that the net metabolic cost of the entire job can be estimated through the summation of the metabolic cost of its individual tasks. Because of the underlying assumption, comparison of work sequences is not possible; thus an optimal solution cannot be found. Furthermore, this assumption has been debated and found to be inapplicable in some MMH activities referred to as Combination Manual Material Handling (CMMH) (Jiang, Smith, & Ayoub, 1986; Straker, Stevenson, & Twomey, 1997; Taboun & Dutta, 1989), which are MMH activities carried out in combination. CMMH, which is a combination of two or more MMH activities at a given time, is a utilization of a variety of muscle groups at varying degrees as dependent on the activities. This utilization of muscle groups may impact the development of fatigue in

CMMH work, which has shown to be more stressful than single MMH activities (Jiang et al., 1986).

Because of the differences in metabolic costs between available MMH prediction models and the costs seen with combined activities, there is a need for additional research on CMMH, as called for by Iridiastadi & Aghazadeh (2005), especially since CMMH is more common in industry than single MMH activities, on which most MMH research has been based. Furthermore, there is an additional research need for the effect that varying task sequences might have on the development of whole-body fatigue in these CMMH activities. Therefore, the purpose of this study was to evaluate the impact varying work intensity sequences have on the time-dependent elements of whole-body fatigue development in a simulated order picking scenario. The scenario investigated in this study incorporates pulling, turning, carrying, and pushing while handling a load at the knuckle-to-knuckle height level. This study addressed two objectives, and the design of the study allowed these objectives to be carried out in conjunction with each other.

Objective - 1

The purpose of this portion of the study was to evaluate the impact varying the preceding workload ("baseline") has on the whole-body fatigue development for varying subsequent workloads (2.3 kg (5 lb), 6.8 kg (15 lb), and 11.4 kg (25 lb) packages at 10/min; "Very Low", "Low", and "Moderate", respectively):

<u>Hypothesis 1:</u> Steady state whole-body fatigue (%HRR) for workload is not affected by preceding workload.

H_0: $\mu_{\text{Peak \%HRR for workload with 'Resting' baseline}} = \mu_{\text{Peak \%HRR for workload with 'Very Low' baseline}} = \mu_{\text{Peak \%HRR for workload with 'Low' baseline}} = \mu_{\text{Peak \%HRR for workload with 'Moderate' baseline}}$

H_1: $\mu_{\text{Peak \%HRR for workload with 'Resting' baseline}} \neq \mu_{\text{Peak \%HRR for workload with 'Low' baseline}} \neq \mu_{\text{Peak \%HRR for workload with 'Moderate' baseline}}$

<u>Hypothesis 2:</u> Rate of change (τ) for workload is not affected by preceding workload.

H_0: $\mu_{\text{T for workload with 'Resting' baseline}} = \mu_{\text{T for workload with 'Very Low' baseline}} = \mu_{\text{T for workload with 'Low' baseline}} = \mu_{\text{T for workload with 'Moderate' baseline}}$

H_1: $\mu_{\text{T for workload with 'Resting' baseline}} \neq \mu_{\text{T for workload with 'Very Low' baseline}} \neq \mu_{\text{T for workload with 'Low' baseline}} \neq \mu_{\text{T for workload with 'Moderate' baseline}}$

<u>Hypothesis 3:</u> Work Pulse $\Delta(HR_{SS} - HR_{Rest})$ (bpm) for workload is not affected by preceding workload.

H_0: $\mu_{\text{Work Pulse for workload with 'Resting' baseline}} = \mu_{\text{Work Pulse for workload with 'Very Low' baseline}} = \mu_{\text{Work Pulse for workload with 'Low' baseline}} = \mu_{\text{Work Pulse for workload with 'Moderate' baseline}}$

H_1: $\mu_{\text{Work Pulse for workload with 'Resting' baseline}} \neq \mu_{\text{Work Pulse for workload with 'Very Low' baseline}} \neq \mu_{\text{Work Pulse for workload with 'Low' baseline}} \neq \mu_{\text{Work Pulse for workload with 'Moderate' baseline}}$

Experimental Design – Objective 1

Randomized block design. Experimental order was determined randomly without repeat:

- Rest → 2.3 kg (5 lb) → 6.8 kg (15 lb) → 11.4kg (25 lb)
- Rest → 2.3 kg (5 lb) → 11.4 kg (25 lb) → 6.8kg (15 lb)
- Rest → 6.8 kg (15 lb) → 2.3 kg (5 lb)

- Rest → 11.4 kg (25 lb) → 2.3 kg (5 lb)

A within-subject design was used with:

Independent variable

- Baseline work rate: Resting, Very Low (2.3kg (5 lb)), Low (6.8kg (15 lb)), and Moderate (11.4kg (25 lb)) @ 10pkgs/min

Dependent variables

- Steady state fatigue level (% Heart Rate Reserve)
- Fatigue rate (time constant tau)
- Work pulse (beats per minute)

Objective - 2

The purpose of this portion of the study was to evaluate the impact varying very low, low, and moderate work rate sequences has on whole-body fatigue development.

Hypothesis 1: Mean steady state whole-body fatigue (%HRR) is not affected by work rate sequence order.

H_0: $\mu_{\text{Mean \%HRR for incremented sequence}} = \mu_{\text{Mean \%HRR for mixed sequence}}$

H_1: $\mu_{\text{Mean \%HRR for incremented sequence}} \neq \mu_{\text{Mean \%HRR for mixed sequence}}$

Hypothesis 2: Peak steady state whole-body fatigue (%HRR) is not affected by work rate sequence order.

H_0: $\mu_{\text{Peak \%HRR for incremented sequence}} = \mu_{\text{Peak \%HRR for mixed sequence}}$

H_1: $\mu_{\text{Peak \%HRR for incremented sequence}} \neq \mu_{\text{Peak \%HRR for mixed sequence}}$

Hypothesis 3: Rate perceived exertion (RPE) is not affected by work rate sequence order.

H_0: $\mu_{\text{Peak \%HRR for incremented sequence}} = \mu_{\text{Peak \%HRR for mixed sequence}}$

H_1: $\mu_{\text{Peak \%HRR for incremented sequence}} \neq \mu_{\text{Peak \%HRR for mixed sequence}}$

Experimental Design – Objective 2

Randomized block design. Experimental order was determined randomly without repeat:

- Rest – 2.3kg – 6.8kg – 11.4kg (incremented)
- Rest – 2.3kg – 11.4kg – 6.8kg (mixed)

A within-subject design was used with:

Independent variable

- Sequence Order: incremented (2.3kg (5 lb) → 6.8kg (15 lb) →11.4kg (25 lb)); mixed (2.3 kg (5 lb) → 11.4 kg (25 lb) → 6.8 kg (15 lb))

Dependent variables

- Sequence mean steady state level (% Heart Rate Reserve)
- Sequence peak steady state level (% Heart Rate Reserve)
- Rated perceived exertion (RPE) – Borg RPE 6-20 scale

Methods

Pre-Experiment Data Collection and Data Analysis

The purpose of this study was to evaluate the effects the unique work characteristics of an order picking operation would have on fatigue development. In order to fully understand the operation, several observational and data collection visits were made to the Big Lots Distribution Center in Montgomery, AL. During those visits, information was collected pertaining to the layout, the work methods, conditions and characteristics of the work (i.e., work area, boxes, and pallets), and the environment. From those visits the following was discovered:

- Pallets are 0.10m (4") in depth and are staged 1.07m (42") from conveyor.
- Products are contained in boxes or bags of varying sizes and shapes (referred to as 'cartons'). The majority of the cartons were not equipped with handles or handholds.
- The conveyor is 0.76 m (30") in height (from floor).

Real order picking data were later obtained and analyzed to ascertain the distribution of carton weight per assignment. From sixty random assignments (N=865 cartons), it was determined that:

- Frequency of picks per assignment was between eight and twelve boxes per minute.

- 88% of the cartons weighed 11.4 kg (25 lb) or less (Figure 7). In order to evaluate the effects of varying weights lifted representative of the majority seen in the assignments at Big Lots, three weight categories were chosen to represent three bin classifications: 2.3 kg, 6.8 kg, and 11.4 kg.

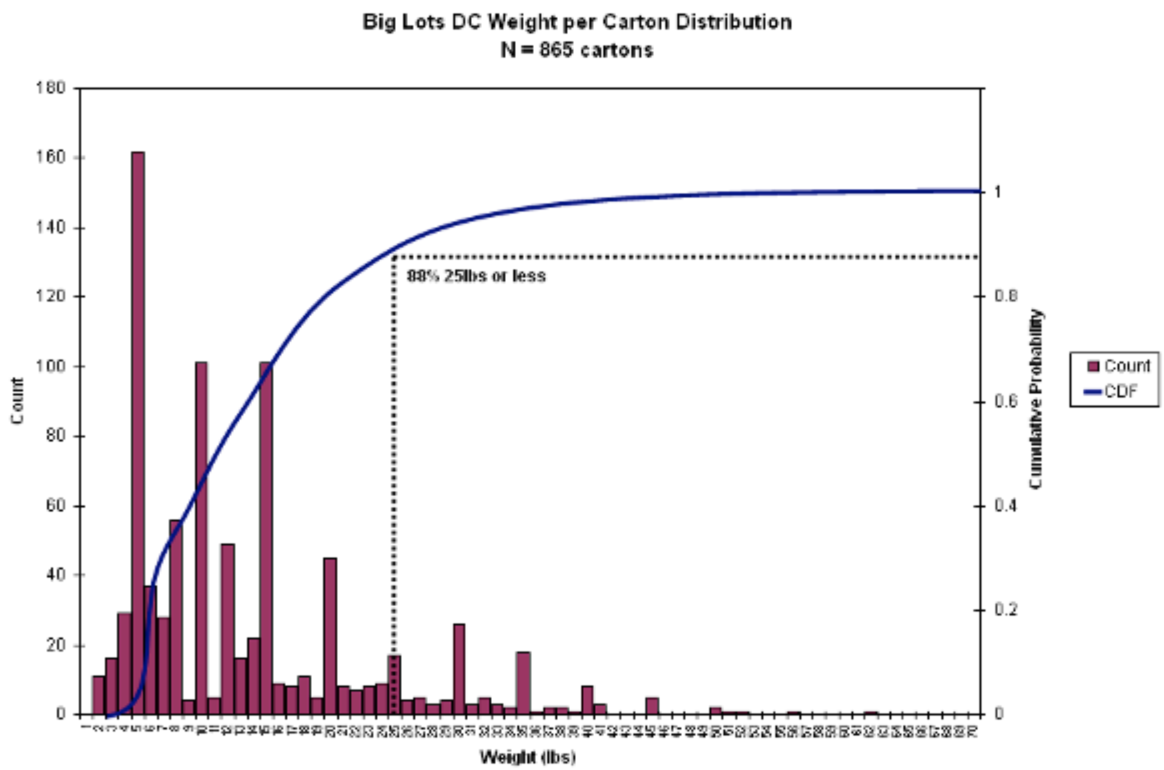


Figure 7: Weight distribution per 60 random assignments obtained from Big Lots DC

Subjects

Twenty three subjects (n = 12 males; 11 females) volunteered to participate in the study (Table 2). Subjects were recruited from Auburn University per the Office of Human Subjects Research Institutional Review Board (IRB) regulations (approved script Appendix 3-A). Incentive for participation was in the form of extra credit for engineering courses. Each subject was informed about the procedures involved in the study, which was approved by the Review Board, before they gave their written consent (Appendix 3-B). Exclusion criteria included those who had a history, symptoms, and/or risk factors associated with contraindication to performing the simulated order picking and was assessed via a health questionnaire (Appendix 3-C) as having a HIGH risk level for an adverse event to the work were excluded from the study. Those with current low back pain, joint (knees & elbows) pain, were pregnant, younger than 19, or older than 65 were excluded from participating as well. No subjects who chose to participate met these criteria, therefore no subjects were excluded. Termination criterion during the trials were if any subject exhibited an elevated heart rate (85% HRR) for 3 consecutive minutes during any part of the trial, however no subjects met this criterion. Subjects were also allowed to stop the trial at any point if they so chose but no subjects opted to do so during the trial.

Table 2
Subject Characteristics (N=21)

	Mean (SD)	Range
Age (yrs)	21.6 (3.8)	19 – 33
Weight (kg)	74.7 (15.0)	52.3 – 99.5
Height (cm)	27.0 (1.5)	24.4 – 29.5
Standing Rest HR (b min^{-1})	86 (16)	52 – 122
HR Reserve (HR_{max}-HR_{Rest}) (b min^{-1})	112 (16)	79 - 147

Experimental Procedure

Four different order picking sequences were evaluated in this study: two three workload sequences (Incremented (INC) = 2.3 kg (5 lb) - 6.8 kg (15 lb) - 11.4 kg (25 lb), Mixed (MIX) = 2.3 kg (5 lb) – 11.4 kg(25 lb) – 6.8 kg(15 lb)) and two sequences with only two workloads: 2.3 kg (5 lb) - 6.8 kg (15 lb), 11.4 kg (25 lb) - 2.3 kg (5 lb). For the study, subjects (two at a time) simulated order picking by picking and placing boxes of the weights in the various sequence order at a set pace (10 boxes/minute) kept via an online metronome until confirmed steady state (American College of Sports Medicine [ACSM] exercise testing protocol (Franklin, Whaley, & Howley, 2000)) for each workload. Subjects moved boxes from one table to another 1.07 m (42") apart, both tables 0.76 m (30") in height from floor (Figure 8); repeating the pick and place cycle for each workload until the sequence was completed.

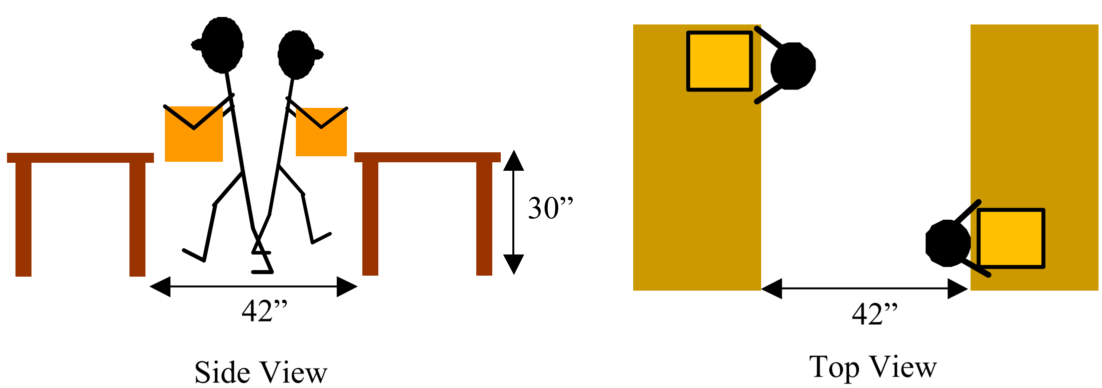


Figure 8: Side and Top view of experiment layout

Once heart rate transmitting equipment had been donned, subjects stood quietly still for 5 minutes at which time resting heart rate was recorded on a data collection sheet (Appendix 3-D). During standing rest time, the subjects received instructions on the experiment which included details on the setup, metronome pace signals, proper lifting techniques, and explanation of RPE (Appendix 3-D). Prior to commencement of the lifting trial, the subjects randomly chose the sequence order for the trial. All sequences were completed in one session.

For each sequence, the subjects began picking at the command of the investigator and continued to pick until both subjects heart rate reached steady state which was considered as such if the current heart rate was +/- 6 beats per minute of the heart rate recorded at the previous one minute mark (Franklin et al., 2000). Once at steady state, the subjects picked the next weight in the sequence, which was staged by the investigator, until steady state. This was continued until the current sequence was completed, at which time the subjects stood quietly while recovery heart rate was noted every thirty seconds after cessation to determine when initial resting heart rate was met. Upon reaching resting heart rate, the next previously chosen sequence was initiated. This protocol continued until all possible sequence combinations were exhausted.

In an effort to minimize variability of the study, certain control measures were employed in addition to the non-varied task characteristics of the study (i.e., box size and condition, distance of carry, and pace). Boxes were not equipped with handholds to mimic real world situations, and subjects were allowed to determine how they secured the load (i.e, grip the sides or the bottom). However, subjects were instructed to handle boxes by getting close to the load, securing it close to the body, and pivoting (avoid twisting) to minimize injury risks. And this was constantly monitored throughout the study with verbal cues supplied as necessary. The speed of the carries was controlled by the audible metronome; although some subjects deviated slightly at times. When this occurred the investigator encouraged the subject to keep pace with the metronome. To control for any previous outside activities, subjects were asked to refrain from any moderate to heavy exercise and caffeine intake 24 hours prior to the study, and they were instructed to wear comfortable clothing the day of the study. To minimize any environmental effects, the activity took place in a temperature controlled laboratory (average temperature was noted as 70.0°F).

Equipment and Measurements

Like oxygen consumption, heart rate is an indicator of physical capacity and changes in heart rate can be a good reflection in the physiological response to work. By evaluating the heart rate elevation above the resting values, a reasonable assessment of the workload can be made (Chengalur, Rodgers, & Bernard, 2004). Because it is less invasive than its oxygen consumption counterpart, it is a widely used fatigue assessment measure in research. Heart rate monitoring technology has advanced, making the collection of heart rate data and its corresponding kinetic information easy and quick. For this study, subjects wore a Polar T31-CODED transmitter (Figure 9), which is coded to a specific Polar RS800 Heart Rate Monitor (Figure 10), around their chest in order to wirelessly capture the time-dependent heart rate data. This transmitted data were recorded every five second (5s) at the commencement of the lifting trials and later retrieved via a compatible IRA/USB interface (Figure 11) and downloaded for further analysis. Prior to the trials, the heart rate monitors were synchronized and the start and end time of each trial was noted. Due to the non-interference design of the transmitters and monitors, two subjects per trial period were able to be evaluated to aid in the logistics of the study.

Figure 10: Polar T31-CODED transmitter

Figure 9: Polar RS800 heart rate monitor

Figure 11: Polar IRA/USB

The 6-20 Borg-scale (Borg, 1985) was used to determine the rate of perceived exertion (RPE) after each sequence.

Additional equipment included:

- 0.76 m (30”) table
- 0.4 m(16”) x 0.32 m (12.5”) x 0.32 m (12.5”) boxes <u>without</u> handles (weighted with bricks and shipping peanuts to stabilize)
- Web-based metronome (webmetronome.com)
- Stopwatch
- Weight and height scale

Data Reduction

All data were visually inspected after transfer from their respective collection devices to the computer. Also, data were correlated to start and end times noted during the data collection process. Readings not associated with the trials (monitors recorded during the entire session) were excluded from data analysis. From the recorded heart rate values, the individual's relative % heart rate reserve (%HRR) was calculated using the following formula (Karvonen, Kentala, & Mustala, 1957):

$$((HR - HR_{Rest}) / (HR_{Max} - HR_{Rest})) \times 100$$

Data Analysis and Statistics

To evaluate the differences in the mean physiological responses between the three preceding workloads and between the sequences, repeated measures ANOVA was performed with a Tukey-Kramer post hoc test used to further evaluate differences identified by the ANOVA. For sequence pairs identified as having a significant difference for the respective physiological response means, a paired Student's *t*-test was performed to further evaluate the differences, as well. To assess the rate of change in the heart rate responses, the time constant tau (τ) was determined by conducting non-linear regression using an exponential one-phase association (or decay, as necessary) equation with a least squares fit (1000 iterations) on the calculated %HRR recorded every 5 seconds throughout the lifting trials. The differences between the time constants for each workload were then evaluated using repeated measures ANOVA and the Tukey-Kramer post hoc test; followed up with a paired Student's *t*-test. The data comparison between the sequence RPEs was performed using a Friedman's test and a

Dunn's post hoc test. For sequence pairs identified as having a significant difference for the RPEs, a Wilcoxon matched pairs test was performed to further evaluate the differences. GraphPad Prism 5.1 statistical software (GraphPad Software, La Jolla, CA) was used to conduct the statistical analysis. Significance level was set at $p < 0.05$. Results are reported as mean (SD).

Results

The principle results of the study are reported in Table 3 and Table 4. When the INC and MIX sequences were compared, there were no significant differences found with respect to the mean %HRR or peak %HRR ($p = 0.5710$ and $p = 0.5791$, respectively). In fact, the mean values were essentially the same in both cases (INC: 12.2 (7.2)% vs. MIX: 12.8 (7.7)% for the mean %HRR and INC: 24.0 (12.1)% vs. MIX: 24.7 (10.5)%). Nor were there any differences found between the perceived exertions ($p = 0.0571$) as seen in Table 3. An illustration of the heart rate responses (%HRR) of one subject throughout the duration of both sequences is shown in Figure 12.

Table 2
Mean and Peak %HRR and RPE for the incremented (INC) and mixed (MIX) sequences (N=23)

	INC (5 lb - 15 lb - 25 lb)	**MIX (5 lb – 25 lb – 15 lb)**
Mean HRR (%)	12.2 (7.2)	12.8 (7.7)
Peak HRR (%)	24.0 (12.1)	24.7 (10.5)
RPE	12.5 (2.6)	11.7 (2.0)

No significant differences were found.
Level of significance ($p = 0.05$)

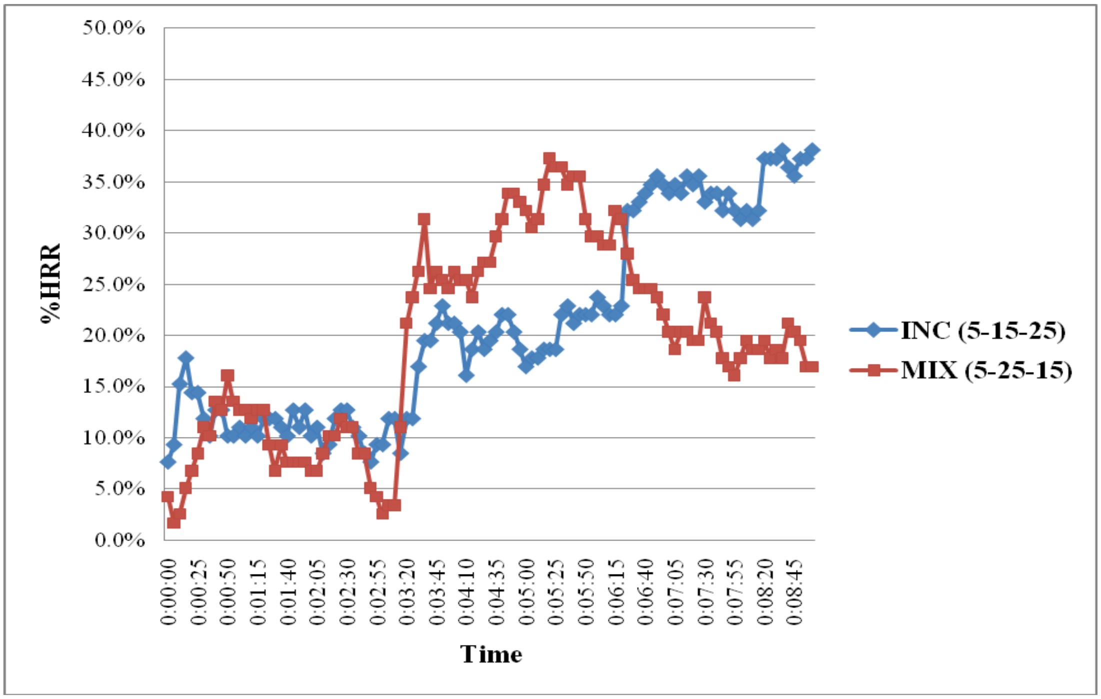


Figure 12: %HRR though out the duration of the INC and MIX sequences for a representative subject.

There were no significant differences found between the %HRR at steady state when the preceding workload was altered ($p > 0.05$) (Table 4). Similarly, there were no significant differences in the rate of change (represented by the time constant τ) nor in the work pulse responses to the workloads when the preceding workload was altered ($p > 0.05$) (Table 4).

Table 3

Mean %HRR at steady state, time constant (τ), and work pulse for each workload following the various preceding workloads (N=23). Average of all subjects.

		From REST	**From 5 lb**	**From 15 lb**	**From 25 lb**
HRR at SS (%)	5 lb	7.8 (8.1)	--	7.5 (7.9)	8.3 (5.2)
	15 lb	6.9 (5.5)	11.3 (7.7)	--	13.1 (8.0)
	25 lb	17.7 (9.3)	19.0 (11.4)	21.0 (11.0)	--
Time Constant τ (s)	5 lb	30.4 (39.1)	--	34.2 (41.7)	42.6 (63.6)
	15 lb	17.5 (26.8)	31.7 (39.0)	--	44.3 (42.9)
	25 lb	21.7 (16.5)	29.7 (26.0)	33.0 (54.9)	--
Work Pulse (b min^{-1}) $\Delta(HR_{SS} - HR_{Rest})$	5 lb	8.4 (8.2)	--	8.5 (7.6)	8.6 (9.8)
	15 lb	12.3 (9.7)	10.0 (8.2)	--	6.2 (8.1)
	25 lb	19.3 (9.5)	21.3 (10.9)	20.6 (10.9)	--

* ($p < 0.01$)
[a] significantly different from 'From REST' ($p < 0.05$)
[b] significantly different from 'From 5 lb' ($p < 0.05$)
[c] significantly different from 'From15 lb' ($p < 0.05$)
[d] significantly different from 'From 25 lb' ($p < 0.05$)

Discussion

The purpose of the this study was twofold: 1) determine if varying the order of workloads within a CMMH task sequence would have a significant impact on various physiological responses; and 2) determine if a very low to moderate intensity preceding workload has an effect on the subsequent very low to moderate intensity workload. The present study was designed such that both objectives could be carried out simultaneously. Prior to discussing the results, the limitations should be noted. In an effort to represent a real world order picking scenario as best as possible in a laboratory setting, prior data analysis was conducted at the Big Lots Distribution Center in Montgomery, AL. From that investigation, the layout, weights, and package characteristics included in this study where chosen. However, these elements do not fully encompass the varied activities and package characteristics experienced by the order pickers at the facility. The duration of the picks, controlled in this study, was observed to be extremely variable, essentially making this type of work "non-steady state" with respect to both duration of the pick and work intensities. However, only non-steady state work intensities were evaluated here with duration held constant. Furthermore, the pick and place activity from a knuckle height to knuckle height level was selected to investigate a "best case scenario." But this type of work was determined to be at most only moderately fatiguing.

An additional limitation to the study was the use of %HRR. The participants within the study were relatively close in age (range 19 – 33). However, the recruitment age range was considerably higher (range 19 – 65). Given that age is a factor in the determination of the heart rate reserve due to the use of the estimated HR_{Max} equation (220-age), the impact from such a possible vast age range may not have been fully exhibited in this study; especially considering that the average heart rate reserve of the participants was 112 with a s.d. of 16. Additionally, the fitness level of the subjects, which was not evaluated as part of this investigation, could have affected the %HRR given that fitness level could be reflected in the individual's resting heart rate or their heart rate response to the workload. However, the participants were recruited from a college campus and by nature of the environment the participants were assumed to be fairly active. Nevertheless, because of the design of the study, the workloads (5 lb – 35 lb) were the same for each subject as opposed to making the workload relative to the individuals to achieve specific levels of intensities. These limited workloads could have impacted the %HRR of the subjects due to potential differences in their physical fitness.

The finding of this investigation was that performing a very low, low, or moderate intensity series of CMMH tasks does not the alter the heart rate (%HRR), heart rate kinetics (tau), or perceived exertion (RPE) of a subsequent very low, low, or moderate intensity workload. These results did not support the study's hypotheses which stated that these responses would differ as the preceding workload was altered. When the response of the workload in question was compared to when it was coupled with each of the previous, or 'baseline,' workloads, there appeared to be an increasing trend for the 5 lb, 15 lb, and 25 lb. However, these increases were deemed to be insignificant due to the relatively high standard deviation. The results of this study are contrary to what have been seen in investigations evaluating a similar topic. Recent research investigating the impact of varying intensities in cycling exercises reported significant differences in various physiological measures including a significant increase in heart rate when work intensity changed from middle intensity (70% VO_{2Max}) to high intensity (90% VO_{2Max}) (Björklund, Pettersson, & Schagatay, 2007). Studies evaluating the effects of instituting a previous workload prior to a second bout, also known as 'priming,' reported significant differences between the two exercises in both heart rate and heart rate kinetics (De Bruyn-Prevost, 1980; Burnley, Doust, Ball, 2002; Tordi, Perrery, and Harvey, 2003), but the results of this present study did not concur. This disagreement in the results is most likely due to the low level of intensity in this study as compared to the others. In this study, the purpose was to evaluate CMMH tasks which are more likely than not to be low intensity work. The highest yielding %HRR in this study was achieved with the 25 lb workload which exhibited a mean %HRR of just 21.0%. Traditional 'priming' studies center around high-intensity priming exercises >90% VO_{2Max} (Jones, Koppo, and Burnley, 2003) and Björklund et al.'s (2007) study evaluated intensities alternating between 70% VO_{2Max} and 90% VO_{2Max}. Furthermore, the tasks included in this study, as well as CMMH tasks in general, inherently included natural pauses that are utilized as short recovery, or micro-breaks. 'Priming' studies evaluate bouts of continuous exercises during cycling (De Bruyn-Prevost, 1980; Tordi et al, 2003) or treadmill running (Burnley et al., 2002).

An additional finding of the study was that there were no significant differences in the physiological responses when sequence order was rearranged. This, too, did not support the original hypothesis of the investigation. By inference, these results would suggest that varying the sequence order has no impact on the development of whole body fatigue for the intensities and task characteristics included in the design of this study. It is speculated that the reason for no significant difference for any response variable between the sequences is due to the relatively low intensity of the work. The average peak %HRR for the INC and MIX sequences were 24.0% and 24.7%, respectively. The intensities evaluated in the Björklund et al.'s (2007) study were significantly higher (70% and 90% VO_{2max}) than those in the present study.

Conclusion

The results of this study showed that alternating the preceding workload between low intensity workloads had no impact on heart rate related or perceived exertion responses for the subsequent workload. It also showed that when the sequence of low intensity workloads was reordered from an incremented pattern to a mixed pattern, there was no difference in the physiological responses included in this study. The results of this investigation would suggest that low work intensities such as those seen commonly with CMMH work may not benefit from the same positive effects strategic work / exercise ordering has in Fartlek (Graca, 2005) or interval training (Laursen and Jenkins, 2001). Nor do they exhibit similar responses that 'priming' exercises do for high-intensity cycling or running exercises. But this present study did not and could not encompass all the task and workload variations in all the possible combinations for this type of CMMH work and to do so fully would be infeasible. The workloads and activities evaluated for this investigation were chosen to represent real world activities. Opportunities still exist to further understand what effects varying CMMH tasks and sequences have on the potential to minimize MSD injuries through optimization of those tasks and sequences. Therefore, additional CMMH task activity, extended durations, and work intensity combinations, particularly those including lifting and lowering activities which are expected to be more fatiguing, should be evaluated before it can be definitively determined if sequence re-ordering would or would not be beneficial in addressing the risk of developing MSDs in the manual material handling industry.

CHAPTER FOUR

THE EFFECT OF WORK LOAD ORDER ON WHOLE-BODY FATIGUE INDICIES IN COMBINED LIFTING, LOWERING, AND CARRYING ACTIVITIES

Abstract

It was hypothesized that varying the sequence order of workloads in an order picking manual material handling task involving lifting and lowering activities would result in differences in the mean heart rate responses (mean and peak heart rate reserve (%HRR), heart rate time constant (τ)) for the sequences as a whole as well as the individual workloads within the sequences. It was also hypothesized that sequence order would have a significant impact on the whole-body rated perceived exertion (RPE) for the individual workloads and the sequence energy expenditure (EE) collected real time via a Body Media SenseWear Pro armband monitor. Furthermore, it was hypothesized that the collected energy expenditure would be significantly different from the Michigan Energy Expenditure Prediction Program (EEPP) predicted value indicating the inapplicability of summation prediction models in combined manual material handling (CMMH) and/or CMMH work varying in workloads. Twenty-one male and female subjects performed simulated order picking tasks that included lifting, carrying, and lowering four weighted boxes (2.3 kg (5 lb), 6.8 kg (15 lb), 11.4 kg (25 lb), 16 kg (35 lb)) for three minutes each at a rate of 10/min in three sequence orders: (1) incremented, INC (5 lb–15 lb–25 lb–35 lb), (2) mixed, MIX (25 lb–5 lb–35 lb–15 lb), and (3) decremented, DEC (35 lb–25 lb–15 lb–5 lb). The sequence Mean and Peak %HRR was found to be significantly different when the INC and DEC sequence were compared ($p < 0.05$) with the average Mean %HRR for the INC sequence being lower than the DEC sequence (INC: 40.2 (11.7)% *vs.* DEC: 44.5 (16.6)%) and the average Peak %HRR of the DEC sequence being lower (INC: 58.4 (26.9)% *vs.* DEC: 48.7 (22.8)%). Each workload showed a significant difference between at least one sequence order comparison for the heart rate and RPE responses ($p < 0.05$) with the exception of the RPE for the 15 lb workloads. No significant differences were found between any sequence orders for the EE nor between the sequence EE and the EEPP predicted values. The results of this study suggested that sequence order does have a significant impact on heart rate and perceived exertion responses and should be considered in MMH design guidelines as well as a potential means to optimize order picking work to control whole-body fatigue. The results also suggested that sequence order does not impact overall energy expenditure and that it may not be necessary to consider work order in determining the applicability of traditional energy expenditure prediction models. The noted limitations of the study and the limitations of the compared techniques support additional research in this area.

Introduction

In an effort to control the adverse physical responses to manual material handling (MMH) work, several work design recommendations and guidelines have been developed and applied in industry. These guidelines, whether targeted at controlling the biomechanical or physiological hazards of the job, are a product of extensive research that has examined the human body's response to the varying characteristics of MMH, such as lifting, lowering, and carrying. As a result of psychophysical studies conducted by Snook (1978) and Ciriello & Snook (1983), enormous databases are available detailing maximum acceptable weights while lifting, lowering, and carrying as a function of vertical displacement and carrying distances, height level, gender, and frequency. In terms of the physiological responses to lifting, studies conducted by Garg & Saxena (1982), Garg (1983), Mital (1984a, b), and Mital & Fard (1986) outline the maximum acceptable weights with respect to gender, frequency, load characteristics, and lift height and the MAWLs corresponding physiological responses (29 and 28% maximum aerobic capacity for males and females, respectively for an 8-hr shift (Mital, 1984a; Mital, 1984b)).

Although the research for these activities is extensive, it is limiting in that the MMH activities were primarily examined as individual entities and the combined effect, particularly sequencing, of them is not completely understood. This is unfortunate in that a significant amount of MMH work is carried out in a combined activity fashion. One such activity is order picking. In order picking warehouses where product is stored on pallets, operators manually pick and place product from a brick-loaded (i.e., individually stacked in layers) pallet on the floor onto a conveyor system directly behind them. Given that the pallets are stationary in most manual picking warehouse designs (i.e., sans automatic lifts or spring loaded devices), the product's vertical and horizontal pick location can vary significantly from pick to pick. Thus operators are often required to perform a variety of combined MMH activities.

The traditional method of assessing the metabolic cost of such an activity would be to separate the job into subtasks and assess each individually. Total cost of the job would then be determined by applying an additive assumption (Garg, Chaffin, & Herrin, 1978) which assumes that the net metabolic cost of the entire job can be estimated through the summation of the metabolic cost of the individual tasks:

$$\overline{\dot{E}}_{job} = \left(\sum_{i=1}^{n_i} \dot{E}_{pos} \times t_1 + \sum_{i=1}^{n} \Delta\dot{E}_{taski}\right) / T$$

where:

$\overline{\dot{E}}_{job}$ = Average energy expenditure rate of the job (kcal/min)

$\dot{E}_{pos}$= Metabolic energy expenditure rate due to maintenance of i^{th} posture (kcal/min)

t_i = Time duration of i^{th} posture (min)

n_i = Total number of body postures employed in the job

$\Delta\dot{E}_{taski}$ = Net metabolic energy expenditure of the i^{th} task in steady state posture (kcal)

n = Total number of tasks given in the job

T = Time duration of the job

Although this method is widely used in industry, including MMH jobs similar in nature to the order picking job, its underlying assumption has been debated and found to be non-applicable in some combined MMH activities (Jiang, Smith, & Ayoub, 1986; Straker, Stevenson, & Twomey, 1997; Taboun & Dutta, 1989). The reasoning has been because of the utilization of a variety of muscle groups at varying degrees when activities are carried out in combination. This utilization of muscle groups may impact the development of fatigue in this type of work, which has been shown to be more stressful than single MMH activities (Jiang et al., 1986). Due to the complexity of the order picking assignments, these combined activities can be carried out in countless ways.

Another limiting factor of the previous MMH research on lifting, lowering, and carrying is that it did not encompass the changes in work intensity that are intrinsic in order picking. As noted earlier the complexity of the order picking assignments that dictates which and how much of one product is to be picked, which can force the operator to work at a variety of work intensities. Considering that the assignments are developed solely based on the stock-keeping-unit, or SKU, of the product and its location within the layout, work intensities can vary drastically as the weight of the products are not uniform. This added complexity and its effect on the physiological responses to lifting, lowering, and carrying, if understood, has the potential to serve as a method to minimize and/or optimize whole-body fatigue. Therefore, the purpose of this study was to examine the effects work intensity sequence has on the whole-body fatigue responses to combined manual material handling activities including lifting, lowering, and carrying. Also, considering that prediction models are available that can predict the energy expenditure required to carry out MMH jobs, it is unclear if they are applicable to the combined material handling nature of order picking and other similar jobs, nor do they take into account the variable intensity inherent in these types of jobs. Thus, it was the additional intent of the study to examine the applicability of the energy expenditure prediction models' additive assumption to this order picking scenario.

Objectives

The purpose of this study was to evaluate the impact varying workload sequences has on whole-body fatigue development (Heart Rate kinetics, energy expenditure, and whole-body RPE) while lifting, lowering, and carrying loads.

<u>Hypothesis 1</u>: Mean steady state whole-body fatigue (%HRR) is not affected by workload sequence order.

H_0: $\mu_{\text{Mean \%HRR for workload in incremented}} = \mu_{\text{Mean \%HRR for workload in mixed}} = \mu_{\text{Mean \%HRR for workload in decremented}}$

H_1: $\mu_{\text{Mean \%HRR for workload in incremented}} \neq \mu_{\text{Mean \%HRR for workload in mixed}} \neq \mu_{\text{Mean \%HRR for workload in decremented}}$

<u>Hypothesis 2</u>: Peak steady state whole-body fatigue (%HRR) is not affected by workload sequence order.

H_0: $\mu_{\text{Peak \%HRR for workload in incremented}} = \mu_{\text{Peak \%HRR for workload in mixed}} = \mu_{\text{Peak \%HRR for workload in decremented}}$

H_1: $\mu_{\text{Peak \%HRR for workload in incremented}} \neq \mu_{\text{Peak \%HRR for workload in mixed}} \neq \mu_{\text{Peak \%HRR for workload in decremented}}$

<u>Hypothesis 3</u>: Rate of fatigue (tau) for individual workloads is not affected by workload sequence order.

H_0: $\mu_{\text{rate of fatigue for workload in incremented}} = \mu_{\text{rate of fatigue for workload in mixed}} = \mu_{\text{rate of fatigue for workload in decremented}}$

H_1: $\mu_{\text{rate of fatigue for workload in incremented}} \neq \mu_{\text{rate of fatigue for workload in mixed}} \neq \mu_{\text{rate of fatigue for workload in decremented}}$

Hypothesis 4: Whole-body rated perceived exertion (RPE) for individual workloads is not affected by workload sequence order.

H_0: $\mu_{\text{RPE for workload in incremented}} = \mu_{\text{RPE for workload in mixed}} = \mu_{\text{RPE for workload in decremented}}$

H_1: $\mu_{\text{RPE for workload in incremented}} \neq \mu_{\text{RPE for workload in mixed}} \neq \mu_{\text{RPE for workload in decremented}}$

Hypothesis 5: Total energy expenditure (kcal) is affected by workload sequence order.

H_0: $\mu_{\text{EE of incremental sequence}} = \mu_{\text{EE of mixed sequence}} = \mu_{\text{EE of decremented sequence}}$

H_1: $\mu_{\text{EE of incremental sequence}} \neq \mu_{\text{EE of mixed sequence}} \neq \mu_{\text{EE of decremented sequence}}$

Hypothesis 6: Predicted net energy expenditure (kcal) is not affected by workload sequence order.

H_0: $\mu_{\text{Predicted net EE of incremented sequence}} = \mu_{\text{Actual EE of mixed sequence}} = \mu_{\text{Actual EE of decremented sequence}}$

H_1: $\mu_{\text{Predicted net EE of incremented sequence}} \neq \mu_{\text{Predicted EE of mixed sequence}} \neq \mu_{\text{Actual EE of decremented sequence}}$

Experimental Design

Three treatments (picking sequences) were used in this study. Experimental order was determined randomly without repeat:

- 2.3 kg (5 lb) → 6.8 kg (15 lb) → 11.4 kg (25 lb)→ 16 kg (35 lb) (incremented sequence)
- 16 kg (35 lb) → 2.3 kg (5 lb)→ 11.4 kg (25 lb) → 6.8 kg (15 lb) (mixed sequence)

- 16 kg (35 lb) → 11.4 kg (25 lb) → 6.8 kg (15 lb) → 2.3 kg (5 lb) (decremented sequence)

A within-subject design was used with:

Independent variable

- Sequence order: incremented, mixed, or decremented

Dependent variables

- Sequence mean steady state level (% HRR)
- Sequence peak steady state level (% HRR)
- Whole-Body rated perceived exertion (RPE) – Borg RPE 6-20 scale
- Total energy expenditure (kcal)

Methods

In this study, the whole-body fatigue effects while performing lifting, lowering, and carrying activities in combination and with variable work rates sequences was examined. These physiological responses included heart rate kinetics, energy expenditure (‘predicted energy expenditure’ (via Michigan EEPP (Garg et al., 1978)) and ‘actual energy expenditure’ (via body sensors), and peak RPE for the varied sequences.

Pre-Experiment Data Collection and Data Analysis

In order to fully understand the operation, several observational and data collection visits were made to the Big Lots Distribution Center in Montgomery, AL. During those visits, information was collected pertaining to the layout, the work methods, conditions and characteristics of the work (i.e., work area, boxes, and pallets), and the environment. From those visits the following was discovered:

- Pallets are 0.10m (4”) in depth and are staged 1.07m (42”) from conveyor.
- The products are contained in boxes or bags of varying sizes and shapes (referred to as ‘cartons’). Majority of the cartons were not equipped with handles or handholds.
- The conveyor is 0.76m (30”) in height (from floor).

Real order picking data were later obtained and analyzed to ascertain the distribution of carton weight per assignment. From sixty random assignments (N=865 cartons), it was determined that:

- Frequency of picks per assignment was between eight and twelve boxes per minute.
- 97% of the cartons weighed 16 kg (35 lb) or less (Figure 13). In order to evaluate the effects of varying weights lifted representative of the majority seen in the assignments at Big Lots, four weight categories were chosen to represent four bin classifications: 2.3 kg (5 lb), 6.8 kg(15 lb), 11.4 kg (25 lb), and 16 kg (35 lb). This was expanded from the three categories noted in the study detailed in Chapter Three in order to assess increased fatigue levels.

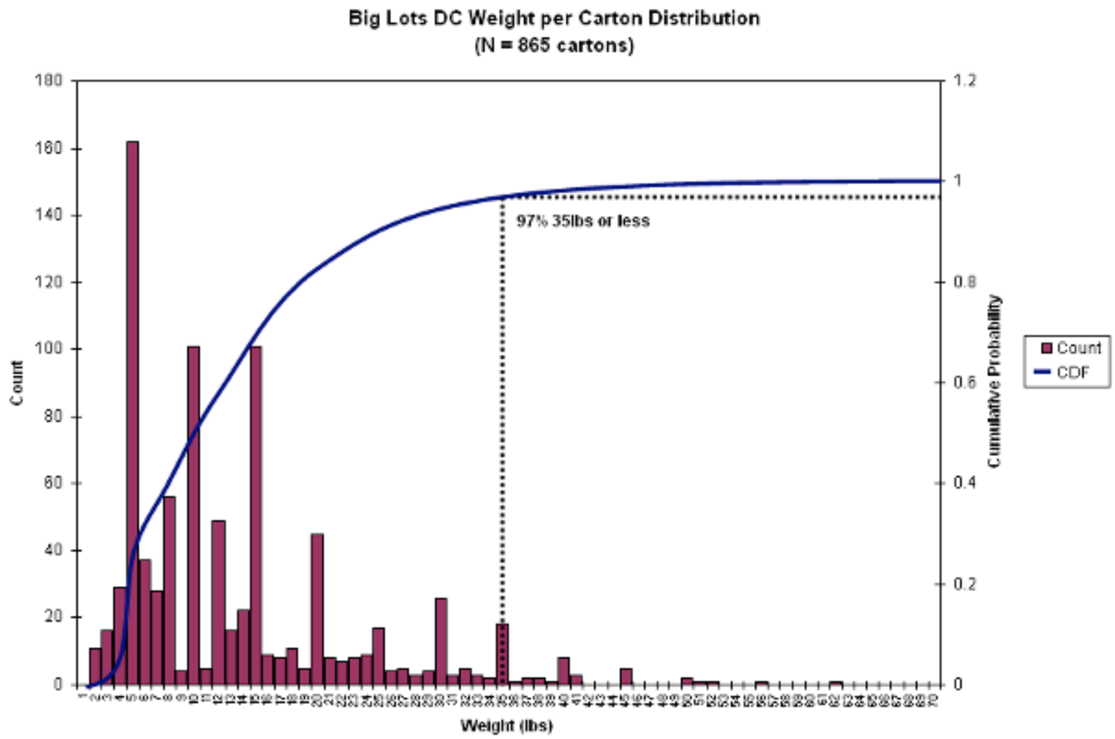


Figure 13: Weight distribution per 60 random assignments obtained from Big Lots DC

Subjects

Twenty four subjects (n = 14 males; 10 females) volunteered to participate in the study (Table 5). Subjects were recruited from the university per an Auburn University Office of Human Subjects Research Institutional Review Board (IRB) policies. Incentive for participation was in the form of extra credit for engineering courses. Each subject was informed about the procedures involved in the study, which was approved by the Review Board, before they gave their written consent (Appendix 4-A). Those who had a history, symptoms, and/or risk factors associated with contraindication to performing the simulated order picking and was assessed via a health questionnaire (Appendix 4-B) as having a HIGH risk level for an adverse event to the work were excluded from the study. Also, those with current low back pain, joint (knees & elbows) pain, were pregnant, younger than 19, or older than 65 were excluded from participating as well. Two perspective subjects were excluded from participating due to meeting an exclusion criterion (current joint pain/injury) and were given an IRB alternative assignment. Termination criterion during the trials was if any subject exhibiting an elevated heart rate (85% HRR) for 3 consecutive minutes during any part of the trial. Subjects were also allowed to stop the trial at any point if they so chose. One subject (female) was excluded from participating in the study having met the prescribed exclusion criterion (sustained elevated heart rate) during two trials and her collected data up to those termination points were not used in the data analysis. Four other subjects (2 males and 2 females), due to reasons unrelated to the study, only participated in part of the experiment (the female subjects completed only one experimental trial for the study and the male subjects each completed two). The data collected for those subjects who completed at least two trials were used for data analysis. Therefore, the total number of subjects equaled 21.

Table 4
Subject Characteristics (N=21)

	Mean (SD)	Range
Age (yrs)	20(0.8)	19 - 21
Weight (kg)	71 (11.7)	43.2 - 98.6
Height (cm)	175 (10.8)	152.7 - 194.7
Standing Rest HR (b min^{-1})	84 (13)	44 – 100
HR Reserve (HR_{max}-HR_{Rest}) (b min^{-1})	115 (13)	99 – 156

Experimental Procedure

Three different order picking sequence orders were evaluated in this study. The order picking scenario consisted of lifting, carrying, and lowering boxes of varying weights in a cycle for three minutes each for a total of 12 minutes for each separate sequence. The sequence orders were as follows: Mixed (MIX)= 11.4 kg (25 lb) – 2.3 kg (5 lb) – 16 kg (35 lb) – 6.8 kg (15 lb); Incremented (INC) = 2.3 kg (5 lb) - 6.8 kg (15 lb) - 11.4 kg (25 lb) – 16 kg (35 lb), and Decremented (DEC) = 16 kg (35 lb) – 11.4 kg (25 lb) – 6.8 kg (15 lb) -2.3 kg (5 lb).

For each subject, the different sequences were completed on three separate days (minimum 12 hours separation) to minimize the fatigue effects between trials and potential musculoskeletal discomfort risk to subjects. The first session began with the collection of the subject's data (age, height, and weight) after which the heart rate monitoring equipment was donned and checked and the sequence for the session was randomly chosen. The subject was instructed to stand quietly for 5 minutes in order to ascertain standing resting heart rate. After the rest, the subjects were fitted with the energy expenditure arm monitor. At the audible and tactile cue of the monitor (chime and vibration noting that the monitor is reading), subjects were instructed to lift, carry, and lower the boxes in the predetermined sequence order and at a constant pace based on the predetermined work measurement of 10 boxes/min (Zandin, 2003) per the following steps: 1) Lift box from 0.10m pallet; 2) pivot and carry box 1.07m (42") to a 0.76m (30") table directly behind; 3) place box in middle of table and then place hands to side; 4) lift box from table; 5) pivot and carry box to pallet directly behind; 6) lower box to pallet and stand with arms to the side; 7) repeat until end of trial. Layout is characteristic of the Big Lots Montgomery, AL facility (Figures 14 and 15). The subject continued to pick the sequence for a total of 12 minutes; switching every 3 minutes to a different weight staged by the researcher.   Whole-Body RPE was recorded at the end of each weight (i.e., collected every 3 minutes). Pertinent data was recorded per data collection sheet in Appendix C. The experiment procedure is shown in a flow chart (Figure 16).

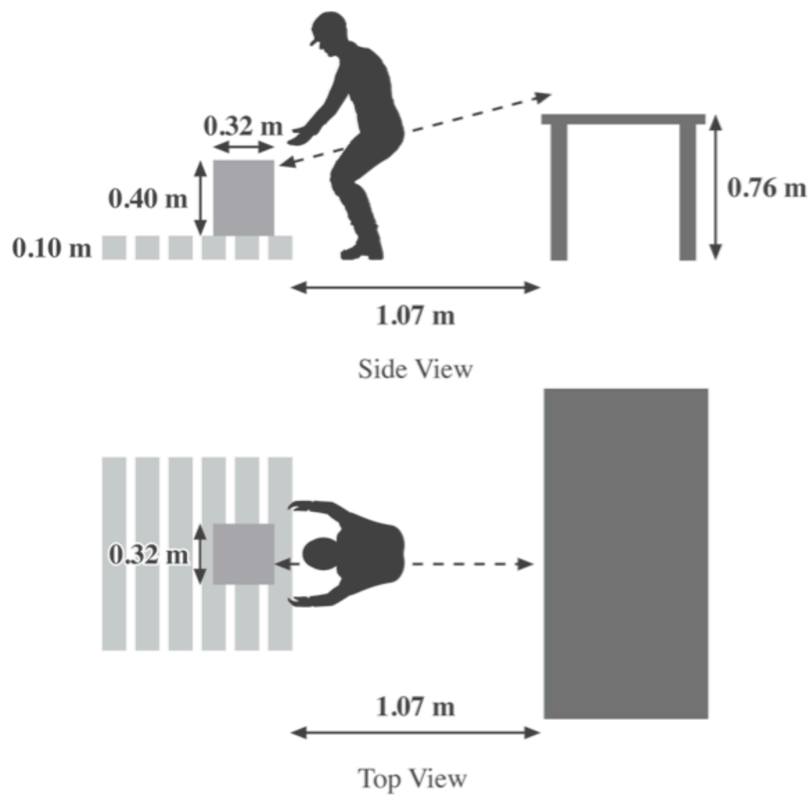


Figure 14: Illustration of the experiment layout (side and top view)

Figure 15: Subjects performing trials

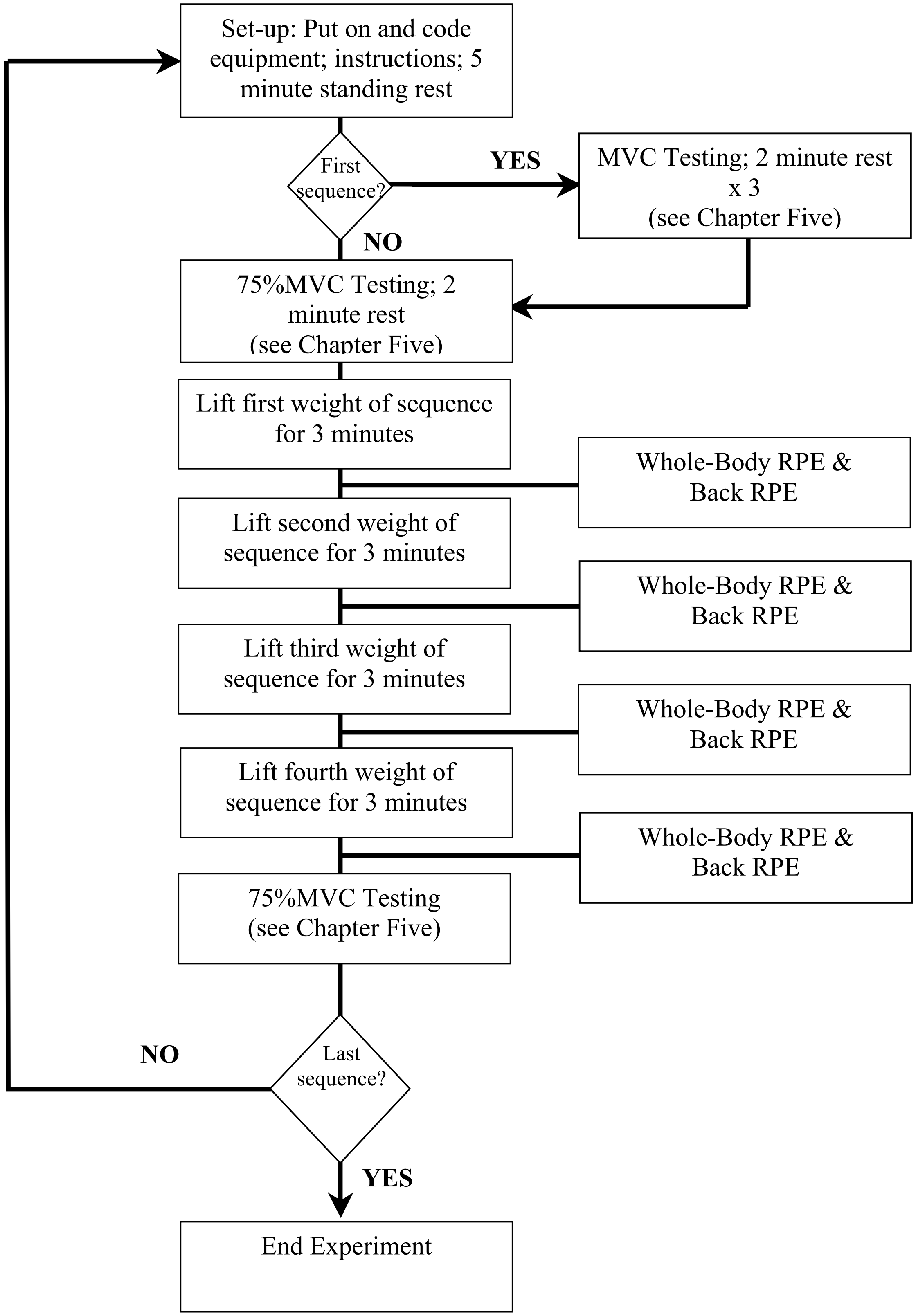


Figure 16: Flowchart of experiment

Subjects were instructed to lift the boxes using a semi-squat posture which was demonstrated prior to commencement of the trials and monitored throughout. Boxes were lifted and lowered on the cue of the metronome tones (picks were made on the first accent; places made on the second accent: http://webmetronome.com/?t=48&b=6&a=100100) and subjects were instructed to keep pace with the audible metronome with the researcher monitoring the pace. The boxes were not equipped with handholds, and it was the subject's preference on how to secure the box while handling it. However, subjects were instructed to keep the load close to their body. The environment temperature was controlled to some extent for all trials and subjects (68.9°F to 71.0°F). All subjects were instructed to refrain from strenuous exercise (running, biking, swimming, weight lifting, or other cardio workouts) and caffeine for no less than 12 hours prior to all study trials and to wear a T-shirt, shorts, and comfortable shoes.

Equipment and Measurements

Like oxygen consumption, heart rate is an indicator of physical capacity and changes in heart rate can be a good reflection in the physiological response to work. By evaluating the heart rate elevation above resting values, a reasonable assessment of the workload can be made (Brouha, 1960). Because it is less invasive than its oxygen consumption counterpart, it is a widely used fatigue assessment measure in research. Heart rate monitoring technology has advanced, making the collection of heart rate data and its corresponding kinematic information quick and easy. For this study, subjects wore a Polar T31-CODED transmitter (Figure 17), which is coded to a specific Polar RS800 heart rate monitor (Figure 18), on their chest in order to wirelessly capture the time-dependent heart rate data. The transmitted data were recorded every second (1s) at the commencement of the lifting trials and later retrieved via a compatible IRA/USB interface (Figure 19) and downloaded to a computer for further analysis.

Figure 17: Polar T31-CODED transmitter

Figure 18: Polar RS800 heart rate monitor

Figure 19: Polar IRA/USB interface

Actual energy expenditure was obtained by means of a less invasive wearable physical activity monitor. These monitors, such as the Body Media SenseWear Armband proposed for use in this study (Figure 20 and 21), have been the subject of several validation studies (Galvani, Andreoletti, Besi, & Faina, 2007; Jakicic et al., 2004; King, Torres, Potter, Brooks, & Coleman, 2004; Wadsworth, Howard, Hallam, & Blunt, 2005) with respect to their ability to effectively estimate energy expenditure (see Feo & Loreto 2005 for a review). The consensus from the studies is that the SenseWear Armband is a valid method for measuring energy expenditure while performing work (exercise). Energy expenditure data were continuously measured every minute with recording of the data beginning at the start of the lifting trials. As with the heart rate data, the recorded energy expenditure data were later downloaded to a computer for further analysis. The 6-20 Borg-scale (Borg, 1985) was used to determine the rate of perceived exertion (RPE) after each workload in the respective sequence trial.

Figure 17: Body Media SenseWear Pro Armband

Figure 18: Subject wearing heart rate transmitter and EE armband

Additional equipment included:

- 0.10 m (4”) pallet
- 0.76 m (30”) table
- 0.4 m (16”) x 0.32 m (12.5”) x 0.32 m (12.5”) boxes without handles (weighted with bricks and shipping peanuts to stabilize)
- Web-based metronome (webmetronome.com)
- Stopwatch
- Weight and height scale

Data Reduction

All data were visually inspected after transfer from their respective collection devices to the computer. Data identified as false or incomplete (such as a failure of the device to read or record due to technical difficulties) was excluded from further analysis. As a result, one energy expenditure data set was eliminated due to the device's failure to correctly store data. From the recorded heart rate values, the individual's relative % heart rate reserve (%HRR) was calculated using the following formula (Karvonen, Kentala, & Mustala, 1957):

$$((HR - HR_{Rest}) / (HR_{Max} - HR_{Rest})) \times 100$$

Energy expenditure data utilized the individual's respective descriptive characteristics (age, weight, height, and gender). The SenseWear monitors collected values every minute and the total value was calculated by summing the values recorded during each minute related to the trials. Because there was the potential for the last workload's activity to carry over into the next minute, which included the individual immediately performing a 75%MVC test (see Chapter 5), the total value included this additional activity (with walk to and from of ~6.1m). These activities were incorporated in the EEPP calculation as well. Experiment activities were inputted into the EEPP that utilized a database containing the following respective regression equations (Garg et al., 1978)):

Standing (kcal/min): $\dot{E} = 0.024B$

Squat lift (kcal/lift): $\Delta E = 0.01[0.514B \times (0.81 - h_1) + (2.19L + 0.62S \times L)(h_2 - h_1)]$

For $h_1 < h_2 \leq 0.81$

Squat lower (kcal/lower): $\Delta E = 0.01[0.511B \times (0.81 - h_1) + 0.7L(h_2 - h_1)]$

For $h_1 < h_2 \leq 0.81$

Carrying, loads held against waist (kcal): $\Delta E = 0.01[68 + 2.54B \times V^2 + 4.08L \times V^2 + 11.4L + 0.379(L + B) G \times V]t$

where:

$\dot{E}$ = energy expenditure;

ΔE = net energy expenditure required for certain movement;

B = body weight (kg);

G = grade of the walking surface (%);

h_1 = vertical height from floor (m) for starting point for lift and end point for lower;

h_2 = vertical height from floor (m) for end point for lift and starting point for lower;

L = weight of the load (kg);

S = gender (1 for males and 0 for females);

V = walking speed (m/sec); and

t = time (min)

Data Analysis and Statistics

To evaluate the differences in the mean physiological responses between the three sequences with respect to the %HRR at the 3 minute mark for each workload and the total energy expenditure for the sequences, a paired Student's *t*-test was performed (listwise deletion utilized to account for missing subject trial data or data deleted due to technical reasons). To assess the rate of change in the heart rate responses, the time constant tau (τ) was determined by conducting non-linear regression using an exponential one-phase association (or decay, as necessary) equation with a least squares fit (1000 iterations) on the calculated %HRR recorded every second throughout the lifting trials. The differences between the time constants for each workload were then evaluated using repeated measures ANOVA and the Tukey-Kramer post hoc test; followed up with a paired Student's *t*-test. The data comparison between the workload Whole-Body RPEs was performed using a paired Wilcoxon matched pairs test (again, listwise deletion utilized to account for missing subject trial data) Graphpad Prism 5.1 statistical software (GraphPad Software, La Jolla, CA) was used to conduct the statistical analysis. Significance level was set at $P < 0.05$. Results are reported as mean (SD).

Results

Heart rate measures and Whole-Body RPE

The principle results of the study are reported in Table 6 and Table 7. There were significant differences found between the INC and DEC sequences with respect to the Peak %HRR (p = 0. 0459) and Mean %HRR (p =0. 0225). When the average responses were compared, the results were conflicting with the INC sequence on average exhibiting a higher %HRR when the Peak %HRR value for the sequences were assessed [INC: 58.4 (26.9)% *vs.* DEC: 48.7 (22.8)%] and the DEC sequence exhibited a higher Mean %HRR value [INC: 40.2 (11.7)% *vs.* DEC: 44.5 (16.6)%] (Table 6). No significant differences were found between the MIX sequence and others.

Table 5

Peak HRR (%), Mean HRR (%) for each sequence. Average of all subjects.

	MIX (n=21)	INC (n=21)	DEC (n=19)
Peak HRR (%)	61.5 (15.3)	**58.4 (26.9)**[c]	**48.7 (22.8)**[b]
Mean HRR (%)	39.0 (13.6)	**40.2 (11.7)**[c]	**44.5 (16.6)**[b]

[*] ($p < 0.01$)

[a] significantly different from MIX sequence ($p < 0.05$)

[b] significantly different from INC sequence ($p < 0.05$)

[c] significantly different from DEC sequence ($p < 0.05$)

Table 7

HRR(%) at 3min, Heart Rate tau(s), and RPE for each workload within each sequence.

	MIX (n=21)				INC (n=21)				DEC (n=19)			
	5 lb	15 lb	25 lb	35 lb	5 lb	15 lb	25 lb	35 lb	5 lb	15 lb	25 lb	35 lb
%HRR at 3min (%)	29.6(14.0)^{c}	43.2(17.5)^{c}	41.1(14.5)^{b,c}	55.1(17.5)^{b}	24.7(9.3)^{c*}	39.6(14.2)	51.4(14.9)^{a}	63.5(17.0)^{a,c}	35.8(14.5)^{a,b*}	45.7(15.7)^{a}	51.1(18.1)^{a}	51.7(19.3)^{b}
Heart Rate τ (s)	31.8(25.7)^{c}	47.1(43.2)	32.0(21.8)^{b}	52.4(42.6)	45.8(36.1)^{c}	65.4(55.3)	66.7(58.7)^{a}	76.9(51.0)^{c}	44.8(39.3)^{a,b}	47.4(48.0)	24.5(24.4)	39.6(23.8)^{b}
RPE	8.4(1.5)^{b}	11.3(1.5)	11.3(1.9)^{b*,c}	14.3(2.1)^{b*,c*}	7.4(1.2)^{a,c*}	10.5(1.7)	13.0(1.5)^{a*}	15.1(1.6)^{a*,c*}	8.7(1.6)^{b*}	10.9(1.6)	12.4(1.8)^{a}	12.6(2.1)^{a*,b*}

* ($p < 0.01$)

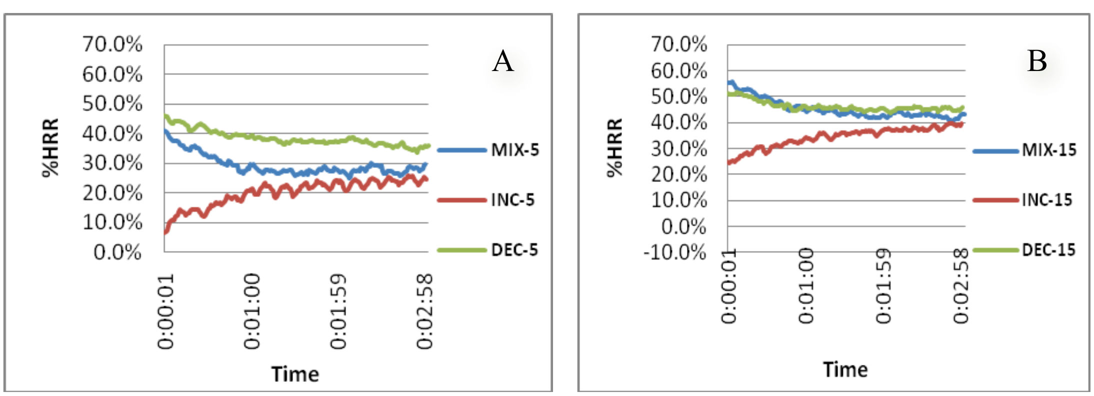
[a] significantly different from MIX sequence ($p < 0.05$)

[b] significantly different from INC sequence ($p < 0.05$)

[c] significantly different from DEC sequence ($p < 0.05$)

For the steady state %HRR (at the 3 minute mark), there were significant differences between specific sequences when the work rates were compared (Table 7). For the 5 lb workload, the INC and DEC sequences were found to be significantly different (p = 0.0006). This workload within the DEC sequence, where it was ordered last in the sequence, exhibited, on average, a higher steady state %HRR [DEC: 35.8 (14.5)% *vs.* INC: 24.7 (9.3)%]. The same was true for when the DEC sequence was compared to the MIX sequence [DEC: 35.8 (14.5)% *vs.* MIX: 29.6 (14.0)%] where the differences were significant (p = 0.0312). For the 15 lb workload, the MIX and DEC were significantly different (p = 0.0419) and the average steady state %HRR in the DEC sequence was slightly higher than the MIX sequence, which was unexpected considering this workload was positioned last in the MIX sequence compared to being second to last in the DEC sequence [DEC: 45.7 (15.7)% *vs.* MIX: 43.2 (17.5)%]. For the 25 lb workload, the %HRR was 24% higher in the DEC sequence when compared to the MIX sequence [DEC: 51.1 (18.1)% *vs.* MIX: 41.1 (14.5)%] where this comparison was found to be significantly different (p = 0.0284). In this case, the 25 lb workload was positioned first in the lower yielding sequence. Similarly, when this workload in the MIX sequence was compared to the INC sequence (p = 0.0194), the INC sequence was 25% higher [INC: 51.4 (14.9)% *vs.* MIX: 41.1 (14.5)%]. Where the 35 lb workload was positioned last as in the INC sequence, the %HRR was on average consistently higher than the other sequences [INC: 63.5 (17.0)% *vs.* MIX: 55.1 (17.5)% and INC: 63.5 (17.0)% *vs.* DEC: 51.7 (19.3)%] and the differences between the sequences were found to be significantly different (p = 0.0197 and p = 0.0036, respectively).

Significant differences in rate of change represented by tau (τ) were found between several of the workloads (Table 7). For the 5 lb workload, where the difference between the MIX and DEC sequences were significant (p = 0.0191), HR τ was seen to be faster for this work rate during the MIX sequence compared to the DEC [MIX: 31.8 (25.7)s *vs.* DEC: 44.8 (39.3)s] when the subject averages were compared. It was found to be faster in the DEC when compared to the INC sequence [DEC: 44.8 (39.3)s *vs.* INC: 45.8 (36.1)s] where this comparison was determined to be significantly different (p = 0.0460). For the 25 lb workload, MIX and INC sequence comparison (p = 0.0441), HR τ was found to be faster, on average, in the MIX sequence where it was positioned first as compared to third in the INC sequence [MIX: 32.8 (21.8)s *vs.* INC: 66.7 (58.7)s]. HR τ was, on average, considerably faster for the 16.0 kg work rate in the DEC sequence compared to the INC sequence [DEC: 39.6 (23.8)s *vs.* INC:76.9 (51.0)s; p = 0.0172]. No significant differences were found between any sequences for the 15 lb workload, (p > 0.05). The trend of average %HRRs for each workload across the lifting trial (3 minutes) are shown in Figure 22.



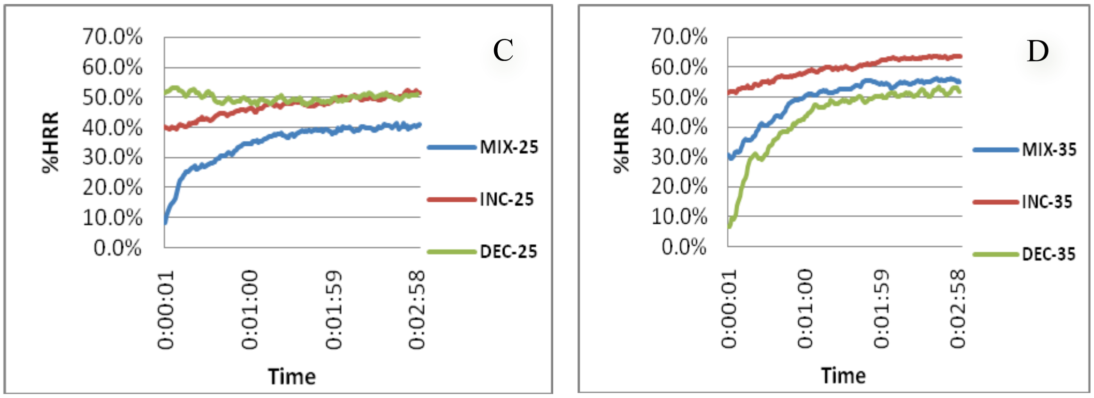
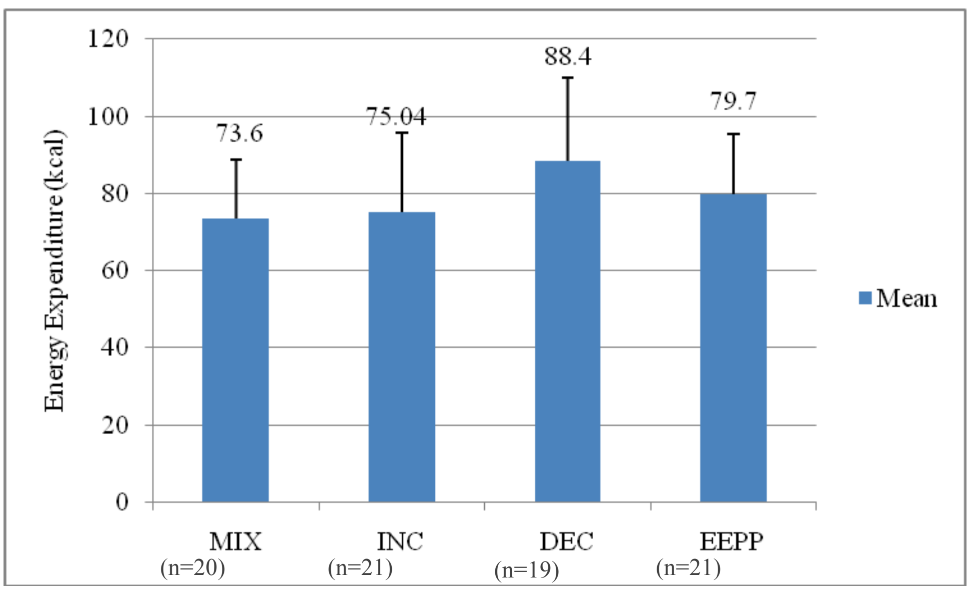


Figure 19: Average %HRR for each workload across the lifting trial (3 minutes); A) 5 lb, B) 15 lb, C) 25 lb, and D) 35 lb. %HRR calculated every second.

Several significant differences were also found between the workloads across the sequences with respect to Whole-Body RPE (Table 7). For the 5 lb workload, the MIX and INC sequences were found to be significantly different (p = 0.0103). The workload in the MIX sequence was found to be more exerting when compared to the same workload in the INC sequence [MIX: 8.4 (1.5) *vs.* INC: 7.4 (1.2)] when the subject averages were evaluated. The workload in the DEC sequence was found to be more exerting as compared to the INC sequence [DEC: 8.7 (1.6) *vs.* INC: 7.4 (1.2)] where the difference was significant as well (p = 0.0023). When comparing the MIX sequence to the DEC and INC sequences, the 25 lb workload in the both the DEC and INC sequences were determined to be, on average, more exerting [DEC: 12.4 (1.8) *vs.* MIX: 11.3 (1.9); p = 0.0340; INC: 13.1 (1.5) *vs.* MIX: 11.3 (1.9); p = 0.0037]. This was to be expected considering that the 25 lb workload was positioned first in the MIX sequence. For the 35 lb workload, the MIX sequence was found to be more exerting than the DEC sequence [MIX: 14.3 (2.1) *vs.* DEC: 12.6 (2.1)] where the difference was significant (p = 0.0009). For the 35 lb workload, the INC sequence was significantly different from both the MIX and DEC sequences ($p = 0.0290$ and $p = 0.0088$, respectively). When the 35 lb workload was positioned last as in the INC sequence, it was found on average to be more exerting than when in the MIX sequence [INC: 15.1 (1.6) *vs.* MIX: 14.3 (2.1)] and the DEC sequence [INC: 15.1 (1.6) *vs.* DEC: 12.6 (2.1)], as to be expected. As with the HR rate of change measure, there were no significant differences between any sequences found for the 15 lb workload ($p > 0.05$).

Energy Expenditure

The total energy expenditure (EE) summed over the entire respective sequence are reported in Figure 23. The ANOVA analysis determined that there were no significant differences found between the sequences nor between any sequence and the predicted values calculated by the Michigan EEPP [79.7 (12.4); $p = 0.5184$].



No significant differences were found

Figure 20: Average energy expenditure values collected real time via the Body Media SenseWear Pro armband monitor worn during the trials for each sequence and the predicted values derived from the Michigan Energy Prediction Program (‘EEPP’). Note: values include the trial plus the final 75%MVC activity (with walk to and from of ~6.1m). Activities included in EEPP values as well. Error bars are SD.

Discussion

The aim of this study was to identify if varying the sequence of the work order in a CMMH task would have an effect on heart rate kinetics, energy expenditure, and Whole-Body RPE responses for the sequences and/or individual workloads. Understanding these responses during this type of work is critical to the efforts to develop effective work controls through sequence optimization to minimize injuries and improve productivity. Traditionally, guidelines and limits in CMMH aimed at controlling adverse health events during this type of work have been based on cardiopulmonary measures. It has been theorized that muscle fatigue rates are minimized when the O_2 deficit of the muscle is reduced by faster oxygen uptake kinetics (Burnley and Jones, 2007). Considering the well known relationship between heart rate and oxygen uptake, controlling these responses could have an impact on the development of muscle related injuries as well. Therefore a better understanding of these responses as they relate to a task representative of a real world CMMH task was warranted.

Prior to discussing the details of the results, limitations to the present study should be noted. Given the time and resources available only three sequence combinations were evaluated in this study. The workloads were representative of loads found at the Big Lots Distribution Center in Montgomery, AL and the sequences were chosen to represent two common patterns: increasing and decreasing; and a varied sequence to illustrate an ad hoc ‘up down’ pattern. The duration of the sequences were limited to 3 minutes per workload as previous studies, not reported here, indicated steady state was met within this time period. Workload in real world situations could be stochastic in terms of intensity and duration (i.e., a heavy intensity workload could last for several minutes followed by a lower intensity workload lasting only for a few seconds, etc…), the purpose of this study dictated that duration of the lifts be controlled. Although effort was made to represent a real world order picking scenario, all the various work related elements involved in the Big Lots Distribution operation were not included in this present study. This included heat and humidity exposure which was observed during initial visits to the site but controlled during this study. Also, package characteristics, such has dimensions, textures, and stability (or lack thereof) were observed to be extremely variable. This variability could possibly impact the method of handling as well potential impacting the physiological responses and only select package attributes (controlled weight, size, and no handles) were included in this study. Lastly, the design of the present study only included lifts and lowers to the pallet located 0.10 m (4”) from the floor to represent a fatiguing situation. However, Big Lots order pickers picked packages from all levels on the pallet, including lifts from the far end of the pallet often times requiring extended reaches as well as lowers from above the shoulder heights; and these picks are done in varying combinations as well. These various pick locations, although not evaluated in this present study, could possibly impact the physiological responses as well.

Another limitation of this study was the use of %HRR, which was relative to the individuals included in this study. Given that the heart rate reserve can be calculated using the age-predicted HR_{Max} equation (220-age), as was used in this study, the age of the subjects would significantly impact their available reserve, and consequently the individual's %HRR for an activity. However, even though the age criterion included in the recruitment for this study was vast (ages 19 to 65), the age range of the subjects that actually participated was much more narrow (ages 19 to 21) and such an impact due to age differences may not have been fully seen. Additionally, an individual's fitness level, which could be reflected in their resting heart rate and/or the extent of the increase in heart rate during the activity, plays a significant role in the determination of the %HRR. For this study, aside from the assessment of contraindications, the overall fitness levels of the subjects were not evaluated. Furthermore, workloads (5 lb – 35 lb) were the same for each subject by design as opposed to making the workload relative to the individuals to achieve specific levels of intensities. These limited workloads could have impacted the %HRR of the subjects due to potential differences in their physical fitness.

The results of the present study showed that sequence order did significantly affect both the mean and peak %HRR between the sequences (INC vs. DEC) when the sequences were assessed as a whole. This would suggest that varying the sequence of the workload within this task may impact the overall level of whole-body fatigue for the combination of work as seen through specific heart rate responses. Furthermore, considering that the INC sequence was significantly lower in terms peak %HRR as compared to the DEC sequence, and vice versa for the mean %HRR response, it further suggests that various responses are relative to sequence patterns. The results of the study also suggested that work order significantly affected the different heart rate measures for the separate workloads. The %HRR was found to be higher for both the 5 lb and 25 lb workload in the DEC sequence when compared to the INC and MIX sequences, respectively, where the changes for the workloads were 11.1% and 10.0%

higher, respectively. For the 35 lb workload, the %HRR was higher in the INC sequence as compared to the MIX and DEC sequences (8.4% and 11.8%, respectively). A steady increasing of heart rate, or heart rate creep, is known to be associated with prolonged activities and it is normally attributed to steady-state work (Niebel & Freivalds, 1999). Such an increase in heart rate was found in studies evaluating the cardiopulmonary responses to steady state exercise (Saltin & Stenberg, 1964). However, a similar drift was seen with high-intensity cycling exercise where varying the intensity was studied (Björklund, Pettersson, & Schagatay, 2007). Although the work in this present study was not steady-state, or comparable to the two high-intensity cyclic pattern of the Björklund (2007) study, heart rate creep was to be expected in this study as well and in all sequences given the duration of the trials. However, the elevated heart rate response in this current investigation was found to vary in the different sequences and in varying magnitude. With the 35 lb workload, in each case of the higher yielding sequence, the workload steadily increased as the sequence progressed. It would be expected that as the workload increased, the heart rate responses would increase as well. However, given the positions of the workloads in the higher yielding DEC sequence where the workloads consistently declined, it is speculated that these increased %HRR as compared to the other sequences may be due to a variation of heart rate creep, where the heart rate is elevated to a point where the decline of the heart rate, even with decreasing work, is slowed. In other words, as workloads decrease the heart rate decreases as well, but not to initial levels (i.e. level reached when starting from resting). The explanation of slowed heart rate decline is very plausible particularly for the 5 lb workload which was preceded by the three previous higher-intensity workloads in the

DEC sequence. Whereas the 5 lb was positioned last in the sequence, the 25 lb workload was preceded only by a single, albeit higher intensity, workload. If this increase by comparison is to be attributed to the slowed heart rate decline, the relatively quick effect after only one preceding workload suggests this slowing of the heart rate decline effect could be immediate. Given that no similar response was seen with the other sequence comparisons for those workloads and that the lower yielding sequence for the 15 lb workload had it positioned last following three workloads of both higher and lower intensities, a specific dose-response relationship may exist and should be further explored.

In addition to %HRR, heart rate kinetics was also significantly affected for the 5 lb, 25 lb, and 35 lb workload. But the results were conflicting as to whether the kinetics were faster after following a higher or lower intensity load. For example, the rate of change (tau) of the 25 lb workload in the MIX sequence, preceded only by standing rest, was considerably faster than when it was in the INC sequence where it was preceded by two lower intensity workloads and the mean %HRR level at the start of that lifting cycle was 39.6%. However, the rate of change for the same workload in the DEC sequence was faster when it was preceded by one higher intensity workload and started with a mean initial %HRR level of 51.7%. Similar results were seen with the 35 lb workload comparisons with similar directional characteristics. This would suggest that the direction of the work, whether increasing or decreasing, influences the speed of the heart rate kinetics. However, for the 5 lb workload, both sequences (MIX vs. DEC) were declining and the mean initial %HRR were essentially the same (41.1% vs. 45.7%; respectively). Despite this, the rate of change for the MIX was 29% faster than the DEC

(31.8s vs.44.8s). This further suggests that in addition to direction, the duration of the preceding work has a significant influence as well. Even though, to date, no study evaluating how varying CMMH activities impact these kinetics are available, similar results (i.e., differing of the kinetics) for other pulmonary indices (oxygen uptake) were found in studies that evaluated the effects of ‘priming’, or introducing prior bouts of high-intensity exercise (Burnley, Jones, Carter, & Doust, 2000). These studies suggest that a previous bout of exercise would ‘speed’ up the oxygen uptake kinetics for the following bout. These studies, besides not being CMMH related, focused solely on identical high-intensity cycle exercises. The results of this present study supported the idea that similar responses could be exhibited by lower intensity CMMH work and in varying workload combinations.

As with heart rate kinetics, significant differences were found in the Whole-Body RPE responses for the 5 lb, 25 lb, and 35 lb workloads. The participants in the study perceived all three of the workloads to be less exerting when the workloads were positioned first in a sequence when compared to when it was positioned after previous work. This suggests that preceding work, be it higher or lower in intensity, does not minimize the perceived fatigue of a subsequent workload. With regards to the MIX sequence, neither the heart rate responses nor the Whole-Body RPE responses indicated that inserting a lighter workload (here, the 5 lb) in between two heavier loads (here, the 25 lb and 35 lb) as a means of ‘active recovery’ made a significant difference in the subjects’ response to the subsequent heavier workload. In fact, the 35 lb workload in the MIX sequence garnered a higher RPE rating as compared to the DEC sequence. This could be due to the fact that the 35 lb load was positioned first in the DEC sequence as compared to the third position on the MIX sequence. The cumulative fatigue from lifting the two previous loads could have been significant enough to elicit a higher rating, despite one of the previous loads being a lighter one. Regardless, the concept of perceiving the load as ‘lighter’ after lifting a heavier load (i.e., lifting 5 lbs after 25 lbs or lifting 25 lbs after 35 lbs) was not exhibited during this study. Therefore, the results do not support the idea that utilizing lighter workloads as active recovery breaks would be an effective means to minimize whole-body fatigue. However, given the limitations of this study, additional research evaluating longer and/or more varied sequences would be beneficial.

The results of the collected energy expenditure indicated that sequence order does not have an impact on the amount of energy expended during a CMMH task. In this study, no sequence was found to be significantly different to another. It also appears that sequence order does not need to be considered in the application of the Michigan Energy Expenditure Prediction Program given that no sequence was found to be significantly higher or lower than the predicted value. This is contrary to other CMMH related studies that found the prediction model to underestimate by as much as 45% (Taboun & Dutta, 1989). In fact, the EEPP was only found to underestimate the DEC sequence by 11%, but this was found to be statistically insignificant ($p = 0.4007$). Even still, 11% is much lower than the difference found in the above study. The reason could be due to the differences in the methods used to determine energy expenditure between this study and other CMMH investigations. In this present study, energy expenditure was collected real time whereas the other studies utilized treadmill aerobic capacity to infer energy expenditure. Although both methods have been validated, both have their own shortcoming with respect to CMMH. Traditional treadmill aerobic capacity testing has been shown to significantly differ when compared to capacity determined through specific CMMH testing (Iridiastadi & Aghazadeh, 2005). And despite the validation studies conducted for armband monitors (Galvani, Andreoletti, Besi, & Faina, 2007; King, Torres, Potter, Brooks, & Coleman, 2004; Wadsworth, Howard, Hallam, & Blunt, 2005), no study has specifically evaluated CMMH activities and one study (Jakicic et al., 2004) suggested that specific activity algorithms should be applied to expenditure values specifically for the monitor utilized in this study; algorithms that have clearly not been developed for CMMH tasks. Therefore, it cannot be asserted that due to the results of this study the Michigan EEPP is not applicable to CMMH tasks that involve workload variations. However, the results do suggest that additional studies further investigating this topic are warranted.

Conclusion

The heart rate and Whole-Body RPE responses in this present study indicate that whole body fatigue, both extent and rate, for this type of CMMH work can be altered by varying work order sequences. Energy expenditure was not shown to be affected. Given the benefits of understanding the heart rate responses and the inferences that could be made with regards to muscle fatigue and consequently MSDs in MMH, further research evaluating the possible dose-response relationships between the workloads and their arrangement for this type of CMMH work is needed, as well as studies evaluating the applicability of prediction models to CMMH tasks as a whole.

CHAPTER FIVE

EFFECT OF WORK SEQUENCE ON LOCALIZED TRUNK MUSCLE FATIGUE & ACTIVITY IN COMBINED LIFTING, LOWERING, AND CARRYING ACTIVITIES

Abstract

Despite the high variability of workload sequences seen in the manual order picking industry due to the varied characteristics of the products handled, no research has evaluated the effect this variability has on the development of localized trunk muscle fatigue or trunk muscle activity. The purpose of the study was to evaluate if the activity patterns and development of muscle fatigue was affected by workload sequence order. Twenty-three subjects performed a simulated lifting and lowering order picking task in three sequence orders: (1) Mixed (MIX): 11.4 kg (25 lb) → 2.3 kg (5 lb) → 16 kg (35 lb) → 6.8kg (15 lb), (2) Incremented (INC): 2.3 kg (5 lb) → 6.8 kg (15 lb) → 11.4 kg (25 lb) → 16 kg (35 lb), and (3) Decremented (DEC): 16 kg (35 lb) → 11.4 kg (25 lb) → 6.8 kg (15 lb) → 2.3 kg (5 lb). Back-rated perceived exertion (Back-RPE) for each workload and surface electromyography of six trunk muscles (right and left erector spinae, latissimus dorsi, and rectus abdominis muscles) and two hamstring muscles (right and left biceps femoris) was collected. Muscle activity (N-EMG) was normalized to the individual's maximum voluntary contraction (MVC). The normalized median power frequency (N-MPF) was collected before and after each sequence. Dynamic

fatigue (Dynamic N-EMG) of each muscle within each workload was determined by evaluating the slope of the peak N-EMG value of the lifting activity at every 33% interval of the 35 lb workload. There was a significant difference in the mean sequence N-EMG for every muscle ($p < 0.05$) with the exception of the right biceps femoris. Each workload showed a significant difference in Back-RPE and N-EMG with at least one sequence pairing for every muscle ($p < 0.05$) with the exception of the left and right biceps femoris in the 15 lb workload and the right biceps femoris in the 25 lb workload in the case of the N-EMG. The only significant difference in static fatigue (MPF) was seen with the right rectus abdominis muscle between the MIX and INC sequence ($p = 0.0010$) and no significant difference was seen between the sequences for any muscle with regards to the Dynamic N-EMG (p < 0.05). The results suggested that optimization of sequence order should be considered as a means to minimize the occurrence of back injuries in the order picking industry.

Introduction

For all injuries reported by the Bureau of Labor Statistics [BLS] in 2007, the back was the most affected (individual) body part, totaling 235,960 injuries in that year (BLS, 2009b). For the 'Laborers and Freight, Stock, and Material Movers' occupation, back injuries accounted for 21.5% of their total injuries for 2007 (BLS, 2009c). The exact cost for back injuries is unclear, but it has been estimated that these injuries cost the U.S. over $13 - $20 billion dollars a year in workers compensation costs (National Academy of Science, 2001). This value only increases when indirect costs such lost work time, training, and lost production is included.

It has been accepted that MMH tasks such as prolonged repetitive lifting, even with light loads, can be a factor in the development of low back disorders and low back pain due to overexertion from excessive fatigue. In terms of localized muscle fatigue, it has been shown that fatigue in muscles can lead to a reduction in their energy absorption capabilities and instability about the joints and spinal column. This lack of structural support can impact the body's ability to securely handle loads through excessive flexion of the structures and increased compression forces to vertebral tissues; even with loads normally considered within 'safe' limits. As noted by Bonato et al. (2003), compressive loads as low as 100N to the spinal column, which are well below the National Institute of Occupational Health's [NIOSH] recommended limit of 3400N, can lead to the spine failure due to lack of muscle support and strength. Therefore, understanding the development of muscle fatigue, especially back muscles predominantly involved in lifting and lowering tasks, is critical to developing effective mitigation solutions to reduce the risk of injury.

Although the exact mechanisms for muscle fatigue are still in debate, it is generally accepted that changes in the exposure to work, whether in the form of work intensity manipulation or complete cessation of work through breaks, alters its development. With repetitive lifting and lowering, back muscle activity (as a group) is affected by the changes in the body's posture as well as the loads that are handled. These kinetic and force changes have been shown to impact the co-activity and recruitment of muscles with varying affects. Gallagher, Marras, Davis, & Kovacs (2002) identified that as posture changes only a subset of trunk muscles are affected, but as the weight of the load increases the recruitment of all available trunk muscles increases. This leads one to the possibility that the varying recruitment patterns seen with posture and load changes could mean variability in the characteristics of activity and/or fatigue development within these individual muscles as well during activities that require these changes.

Although there are several studies that have investigated the effects of repetitive MMH activities on the fatigue of back muscles (Bonato et al., 2003; Dolan & Adams, 1998; Potvin, Norman, & McGill, 1996; Shin & Kim, 2007), including postural changes and load increases, no research is available that addresses the impact of load sequence variability, as seen with order picking and parcel un/loading occupations. Therefore, it is unclear if similar muscle recruitment patterns such as those previously mentioned would be seen in this scenario which could alter the development of fatigue in these muscles. Because of this, it is unclear if an opportunity exists to address and control muscle fatigue development to adverse levels by means of engineered task sequencing. The purpose of this study was to evaluate the recruitment and fatigue development patterns of select trunk muscles while performing lifting, lowering, and carrying activities with variable work rate sequences. The objective was to determine if work order is a candidate for optimization in an effort to control fatigue and therefore minimize injury potential.

Objectives

The purpose of this study was to evaluate if varying workload has an impact on the recruitment and fatigue development patterns of six trunk muscles (right and left erector spinae, latissimus dorsi, and rectus abdominis muscles) and two hamstring muscles (right and left biceps femoris) while performing lifting, lowering, and carrying activities. The following hypotheses are for each of the before mentioned muscles.

<u>Hypothesis 1</u>: Normalized EMG (N-EMG) for each sequence and each workload is not affected by workload sequence order.

H_0: $\mu_{\text{N-EMG for workload in incremental}} = \mu_{\text{N-EMG for workload in mixed}} = \mu_{\text{N-EMG for workload in decremented}}$

H_1: $\mu_{\text{N-EMG for workload in incremental}} \neq \mu_{\text{N-EMG for workload in mixed}} \neq \mu_{\text{N-EMG for workload in decremented}}$

<u>Hypothesis 2</u>: Muscle activity for each sequence and each workload is not affected by workload sequence order.

H_0: $\mu_{\text{Muscle Activity for workload in incremental}} = \mu_{\text{Muscle Activity for workload in mixed}} = \mu_{\text{Muscle Activity for workload in decremented}}$

H_1: $\mu_{\text{Muscle Activity for workload in incremental}} \neq \mu_{\text{Muscle Activity for workload in mixed}} \neq \mu_{\text{Muscle Activity for workload in decremented}}$

<u>Hypothesis 3</u>: Normalized median power frequency (N-MPF) for each sequence is not affected by workload sequence order.

H_0: $\mu_{\text{N-MPF for workload in incremental}} = \mu_{\text{N-MPF for workload in mixed}} = \mu_{\text{N-MPF for workload in decremented}}$

H_1: $\mu_{\text{N-MPF for workload in incremental}} \neq \mu_{\text{N-MPF for workload in mixed}} \neq \mu_{\text{N-MPF for workload in decremented}}$

Hypothesis 4: Subjective Back-RPE for each workload is not affected by workload sequence order.

H_0: $\mu_{\text{Back-RPE for workload in incremental}} = \mu_{\text{Back-RPE for workload in mixed}} = \mu_{\text{Back-RPE for workload in decremented}}$

H_1: $\mu_{\text{Back-RPE for workload in incremental}} \neq \mu_{\text{Back-RPE for workload in mixed}} \neq \mu_{\text{Back-RPE for workload in decremented}}$

Hypothesis 5: Rate of fatigue (Dynamic N-MPF) for each the 35 lb workload is not affected by workload sequence order.

H_0: $\mu_{\text{Rate of fatigue for the incremental sequence}} = \mu_{\text{Rate of fatigue for the mixed sequence}} = \mu_{\text{Rate of fatigue for the decremented sequence}}$

H_1: $\mu_{\text{Rate of fatigue for the incremental sequence}} \neq \mu_{\text{Rate of fatigue for the mixed sequence}} \neq \mu_{\text{Rate of fatigue for the decremented sequence}}$

Experimental Design

A randomized block design of three treatments (picking sequences) was used in this study. Experimental order was determined randomly without repeat:

- 2.3 kg (5 lb) → 6.8 kg (15 lb) → 11.4 kg (25 lb)→ 16 kg (35 lb) (incremented sequence)
- 16 kg (35 lb) → 2.3 kg (5 lb)→ 11.4 kg (25 lb) → 6.8 kg (15 lb) (mixed sequence)
- 16 kg (35 lb) → 11.4 kg (25 lb) → 6.8 kg (15 lb) → 2.3 kg (5 lb) (decremented sequence)

A within-subject design was used with:

Independent variable

- Sequence Order: incremented, mixed, or decremented

Dependent variables

- Normalized EMG (N-EMG)
- Percentage of muscle activity
- Normalized median power frequency (N-MPF); static and dynamic
- Back-RPE
- Rate of muscle fatigue (Dynamic N-MPF)

Methods

Pre-Experiment Data Collection and Data Analysis

The purpose of this study is to evaluate the effects the unique work characteristics of an order picking operation would have on fatigue development. In order to fully understand the operation, several observational and data collection visits were made to the Big Lots Distribution Center in Montgomery, AL. During those visits, information was collected pertaining to the layout, the work methods, conditions and characteristics of the work (i.e., work area, boxes, and pallets), and the environment. From those visits the following was discovered:

- Pallets are 0.10m (4") in depth and are staged 1.07m (42") from conveyor.
- Products are contained in boxes or bags of varying sizes and shapes (referred to as 'cartons'). Majority of the cartons were not equipped with handles or handholds.
- Conveyor is 0.76m (30") in height (from floor).

Real order picking data were later obtained and analyzed to ascertain the distribution of carton weight per assignment. From sixty random assignments (N=865 cartons), it was determined that:

- Frequency of picks per assignment was between eight – twelve boxes per minute.
- 97% of the cartons weighed 16 kg (35 lb) or less (Figure 24). In order to evaluate the effects of varying weights lifted representative of the majority seen in the assignments at Big Lots, four weight categories were chosen to represent four bin classifications: 2.3 kg, 6.8 kg, 11.4 kg, and 16 kg. This was expanded from the three categories noted in the study detailed in Chapter Three in order to assess increased fatigue levels.

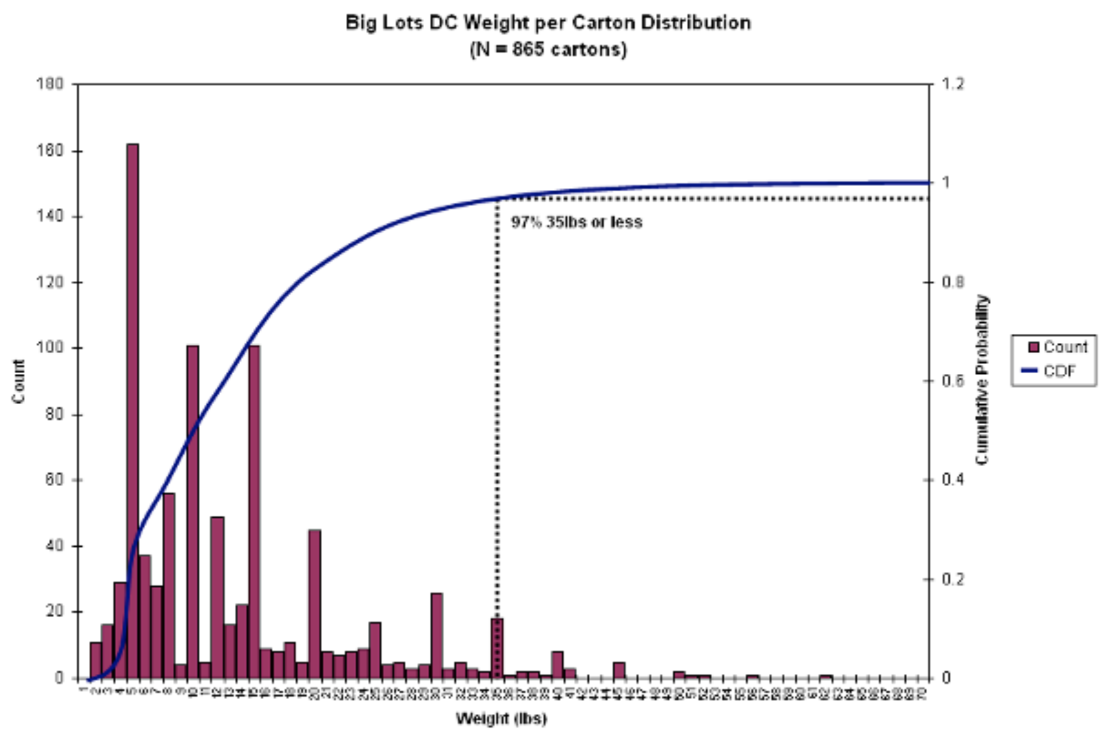


Figure 21: Weight distribution from 60 random assignments obtained from Big Lots DC

Subjects

Twenty four subjects (n = 14 males; n = 10 females) volunteered to participate in the study (Table 8). Subjects were recruited from Auburn University per the Office of Human Subjects Research Institutional Review Board (IRB) policies. Incentive for participation was in the form of extra credit for engineering courses. Each subject was informed about the procedures involved in the study, which was approved by the Review Board, before they gave their written consent (Appendix 5-A). Those who had a history, symptoms, and/or risk factors associated with contraindication to performing the simulated order picking and was assessed via a health questionnaire (Appendix 5-B) as having a HIGH risk level for an adverse event to the work were excluded from the study. Also, those with current low back pain, joint (knees & elbows) pain, were pregnant, younger than 19, or older than 65 were excluded from participating as well. Termination criteria during the trials were if any subject exhibiting an elevated heart rate (85% HRR) for 3 consecutive minutes during any part of the trial. Subjects were also allowed to stop the trial at any point if they so chose. One subject (female) was excluded from participating in the study having met the prescribed exclusion criteria (sustained elevated heart rate) during two trials and her collected data up to those termination points were not used in the data analysis. Four other subjects (2 males and 2 females), due to reasons unrelated to the study, only participated in part of the study (the female subjects completed only one trial while the male subjects each completed two). The collected data of the subjects that completed at least two trials were used for data analysis. Thus the final total of subjects included in the study was 21.

Table 7
Subject characteristics (N=21)

	Mean(SD)	Range
Age	20.1 (0.8)	19 – 21
Weight (kg)	71.4 (11.7)	43.2 – 98.6
Height (cm)	175.3 (10.8)	152.7 – 194.7
MVC (kg)	39.5 (16.0)	11.8 – 76.4

Electromyography, muscle selection, and electrode locations

In order to assess the differences in fatigue development and muscle activity between the three sequences, an 8-channel wireless EMG system (Noraxon TeleMyo™ 2400T Direct Transmission System; Noraxon USA Inc, Scottsdale, AZ) was used (Figure 25 and 26). When muscles fatigue, there is a relative alteration of the EMG spectral activity and this spectral modification can be quantified by tracking a frequency spectrum indicator such as mean frequency (De Luca, 1997). With the EMG system the median power frequency was observed and analyzed for fatigue accumulation as a function of time by means of time-frequency analysis (Bonato et al., 2003). The erector spinae muscles (left and right, LES and RES) are the most commonly evaluated set of muscles when assessing fatigue development in the back during lifting activities. This is mainly because these muscles have been shown to be the most dominant contributors to the loading of the lumbar spine tissues in symmetrical lifts (Potvin et al., 1996). However, additional trunk muscles are involved in the control of flexion and extension, and the overall stability of the spinal structure. These include the left and right latissimus dorsi muscles (LLD and RLD), and the left and right rectus abdominis muscles (LRA and RRA) (Schultz and Andersson, 1981). Additionally, it has been hypothesized that during lifting activities, the hamstrings (primarily the biceps femoris

(LBF and RBF)) can 'pull' upon the pelvis increasing the backward rotation (Lariviere, Gagnon, & Loisel, 2002). Correspondingly, eight pairs of pre-gelled disposable Ag/AgCl bipolar surface electrodes (EME Company) with a 3cm inter-electrode distance were used to collect the EMG of the trunk muscles. For the LRA and RRA muscles, the electrodes were placed 2cm on either side lateral to the umbilicus. The electrodes for the LLD and RLD were placed over the muscle belly ~4cm below the inferior tip of the corresponding side's scapula. Electrodes for the LES and RES were placed 2cm lateral to the L3 spinous process. For the LBF and RBF, the electrodes were placed halfway between the ischial tuberosity and the popliteal. All electrodes were placed parallel to the respective muscle's fiber orientation and pre-cut cardboard for the respective distances were used as an additional guide in the subsequent placement of the electrodes over the course of the study. Prior to placement of the electrodes, the skin was abraded to remove oil and dead skin and rubbed with alcohol to reduce electrode impedance. Furthermore, clothing worn by the subjects suspected to interfere with electrodes (i.e., excessive rubbing) was pinned out of the way or removed at the decision of the subject. EMG signals were recorded at a sampling frequency of 1500 Hz and stored for both real time and later processing using the MyoResearch-XP 1.07 Master Application Protocols software (Noraxon USA Inc, Scottsdale, AZ) which was installed on a personal computer. Gain was set at 400, high-pass filters set to 10 Hz +/- 10% cutoff, CMR > 100 dB, and input impedance > 100 M ohm. A Flip Video Camcorder (Cisco Systems Inc, San Jose, CA) was used to capture movements and later correlate to EMG data.

Figure 22: Noraxon TeleMyo™ 2400T Direct Transmission System

Figure 23: Subject wearing Noraxon TeleMyo™ 2400T Direct Transmission System (electrodes for the left and right bicep femoris muscles not shown)

Experimental Procedure

Three different order picking sequence orders were evaluated in this study. The order picking scenario consisted of lifting, carrying, and lowering boxes of varying weights in a cycle for three minutes each for a total of 12 minutes for each separate sequence. The sequence orders were as follows: Mixed (MIX)= 11.4 kg (25 lb) → 2.3 kg (5 lb) →16 kg (35 lb) → 6.8kg (15 lb); Incremented (INC) = 2.3 kg (5 lb) → 6.8 kg (15 lb) → 11.4 kg (25 lb) → 16 kg (35 lb), and Decremented (DEC) = 16 kg (35 lb) → 11.4 kg (25 lb) → 6.8 kg (15 lb) → 2.3 kg (5 lb).

For each subject, the different sequences were completed on three separate days (minimum 12 hours separation) to minimize the fatigue effects between trials and potential musculoskeletal discomfort risk to subjects. The first session began with the collection of the subject's biographical descriptive data (age, height, and weight) after which the sequence for the session was randomly chosen. The surface electrodes and wireless EMG sensors were then applied. After application of the electrodes and sensors, the subject performed a sub-max contraction for each muscle and a power analysis was performed to analyze the frequency characteristics of raw EMG signals for quality and normality. Adjustments, such as slight reorientation, to the leads and/or the electrodes were made as necessary.

After equipment checks, the subject was instructed to complete a EMG Normalization protocol: using a back/leg dynamometer (Appendix C), the subject conducted a MVC test by pulling up on the back dynamometer handles while maintaining their arms and legs straight and contracting with maximum force holding for 3 seconds. This was done three times with a two minute rest between bouts to reduce effects of fatigue (Caldwell et al., 1974). Verbal encouragement by the investigator was used to elicit the most strength for each pull. The maximum force exerted of the three trials was noted as the subject's MVC. At the end of the final rest, the subjects completed one 7-second 75%MVC followed immediately by a 2 minute rest. Data were recorded on data collection sheet in Appendix 5-C. On the sue of the researcher subjects were instructed to lift, carry, and lower the boxes in the predetermined sequence order and at a constant pace based on the predetermined work measurement of 10 boxes/min (Zandin, 2003) per the following steps: 1) Lift box from 0.10m pallet; 2) pivot and carry box 1.07m to a 0.76m table directly behind; 3) place box in middle of table and then place hands to side; 4) lift box from table; 5) pivot and carry box to pallet directly behind; 6) lower box to pallet and stand with arms to the side; 7) repeat until end of trial. Layout is characteristic of the Big Lots Montgomery, AL facility (Figs 27 and 28). The subject continued to pick the sequence for a total of 12 minutes; switching every 3 minutes to a different weight staged by the researcher. Back-RPE was requested at the end of each weight (i.e., collected every 3 minutes). Immediately after completing the sequence, the subject completed another 7-second 75%MVC and the trial session was completed. The above steps were repeated, with the exception of the MVC testing, for the remaining trials which were completed during a separate session separated by a minimum of 12 hours. Every effort was made to schedule sessions for the subjects so that trials occurred during the same time of day (within 2 hours). The experiment procedure is shown in a flow chart (Figure 29).

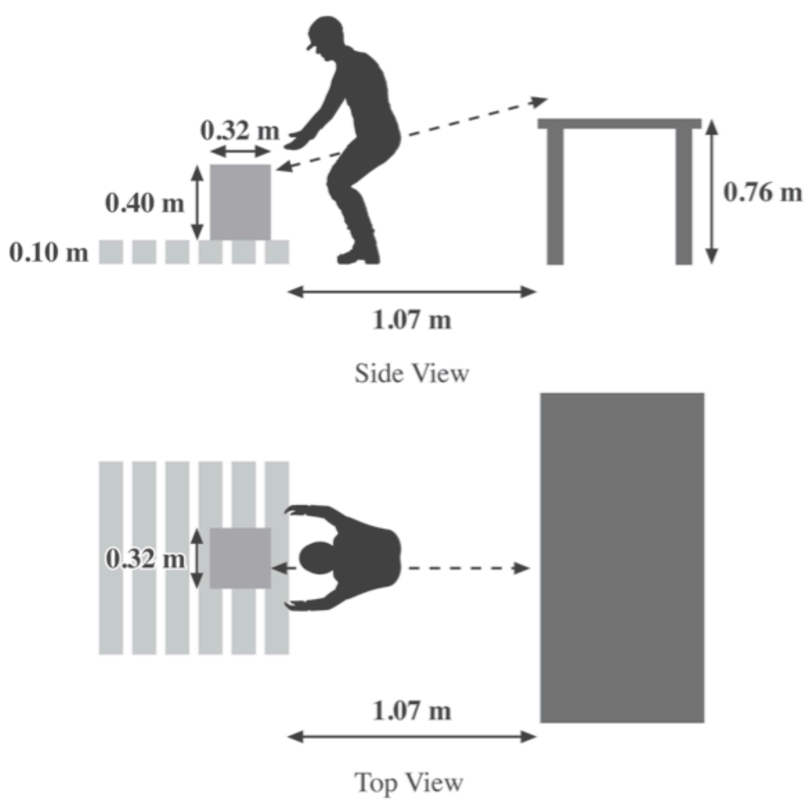


Figure 24: Illustration of the experiment layout.

Figure 25: Experiment layout

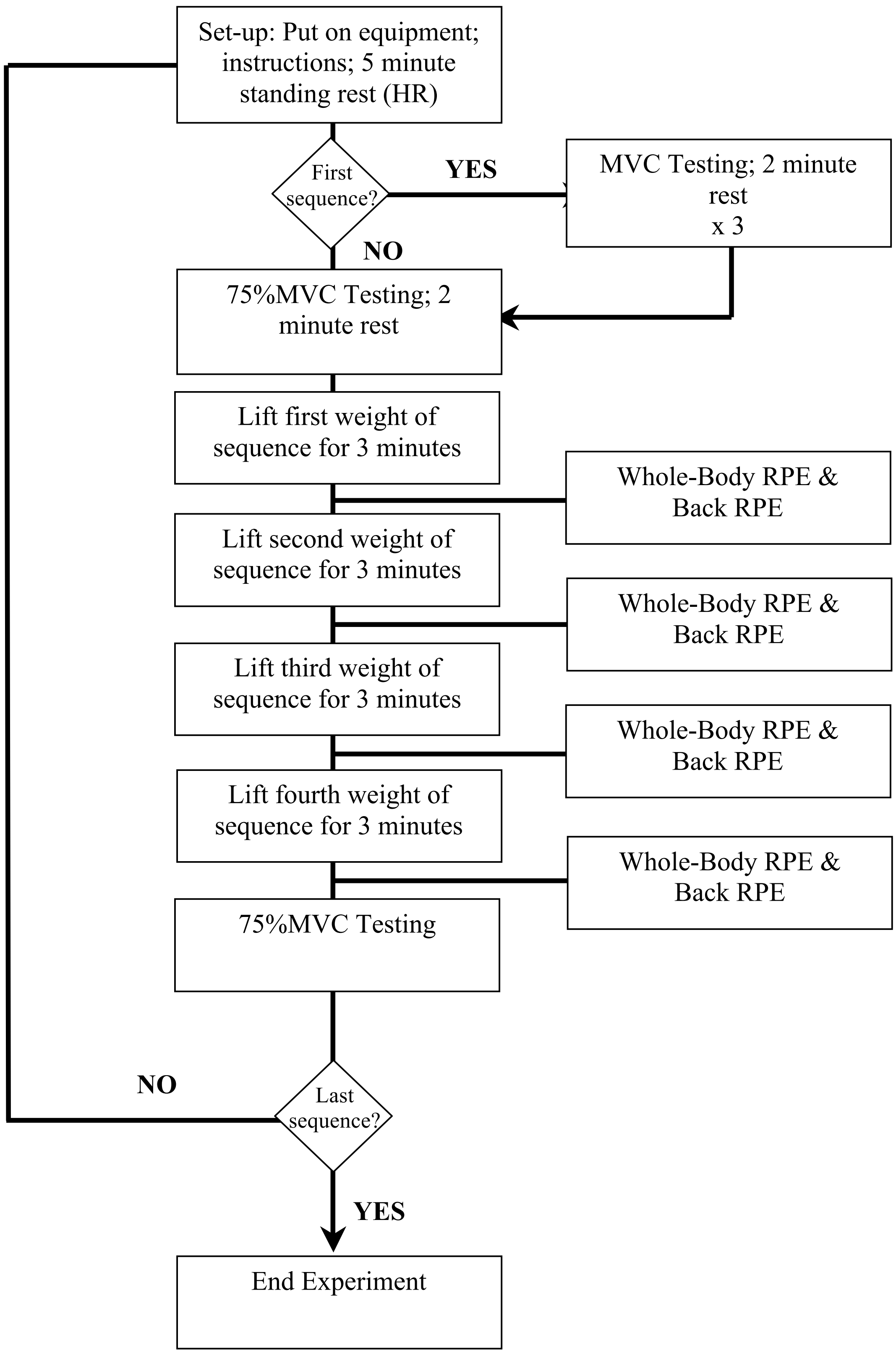


Figure 26: Flowchart of experiment

Subjects were instructed to lift boxes in a semi-squat posture and were constantly monitored throughout the study to ensure this lifting method is maintained. This lifting method has been noted to exhibit lower EMG signal amplitudes of the erector spinae when lifting objects from low levels, and it was recommended as the best posture to minimize biomechanical stress during a lifting task (Chen, Yang, Ding, & Wang, 2004). This lifting posture was demonstrated prior to commencement of the trials. Boxes were lifted and lowered on the cue of the metronome tones (picks was made on the first accent; places was made on the second accent: http://webmetronome.com/?t=48&b=6&a=100100) and subjects were instructed to keep pace with the audible metronome with the researcher monitoring the pace. The boxes were not equipped with handholds, and it was the subject's preference on how to secure the box while handling it. However, the subjects were instructed to keep load close to their body. The environment temperature was controlled for all trials and subjects (68.9°F to 70.9°F). All subjects were instructed to refrain from strenuous exercise (running, biking, swimming, weight lifting, or other cardio workouts) and caffeine for no less than 12 hours prior to all study trials and to wear a T-shirt, shorts, and comfortable shoes.

Measurements

To evaluate muscle fatigue and activity, the raw EMG signals were normalized for each subject through an initial Maximum Voluntary Contraction (MVC) test. MVC and 75% MVC fatigue testing for the trunk muscles (LRA, RRA, LLD, RLD, LES, RES, LBF, RBF) was conducted via a back dynamometer depicted in Figure 30 and 31.

Figure 27: Back dynamometer

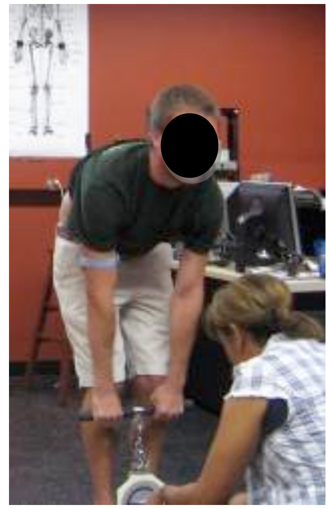


Figure 28: Subject conducting MVC

Additional equipment included:

- 0.10 m pallet
- 0.76 m table
- 0.4 m (12.5”) x 0.32 m (12.5”) x 0.32 m (12.5”) boxes <u>without</u> handles (weighted with bricks and shipping peanuts to stabilize)
- Web-based metronome (webmetronome.com)
- Stopwatch
- Weight and Height scale

Signal Processing and Data Reduction

To correct for any intra-subject differences, all EMG data were normalized and reported as a percentage of the subject’s MVC determined at the beginning of the study. This was converted automatically via the MVC application protocol within the

MyoResearch-XP software. All raw EMG signals, with the exception of signals produced during the 75%MVC activities, were full wave rectified, smoothed (mean, 250 ms), and filtered (low-pass 2.7 Hz and Butterworth) including the initial MVC protocol signals. ECG processing was also applied to all signals to reduce heart rate artifacts. For the 75%MVC activities, a steady 3 second portion of the raw EMG for each 7 second trial of each muscle was analyzed to ascertain the normalized median power frequency (N-MPF). To calculate the %Difference in the beginning and ending static fatigue, the intercepts determined from the linear regression trend line for the median power frequencies were used to further normalize this measure: (Intercept $_{beginning}$ – Intercept $_{end}$)/Intercept $_{beginning}$) *100). To assess muscle activity and illustrate a time history of change to infer the rate of muscle fatigue during the dynamic portion of the trial, the Dynamic N-EMG (in %MVC) of the 35 lb workload at 0%, 33%, 66%, and 100% of the 3 minute cycle (first lift, at 60 second mark, 120 second mark, and last lift) were analyzed. Each of these lifts, determined at the starting point of vertical movement with load in hand, was identified via markers and correlation with video. The processed signals were divided into 250 ms segments and the average EMG amplitude (in %MVC) was calculated for each segment. The valued calculated for the first 250 ms, which signified the start of the lift, was used to compare the sequences at each 33% interval of the cycle for each muscle. The slope of the lifts was calculated (Dynamic N-EMG) to represent the rate of fatigue. Due the extensive data reduction and correlation required to determine these dynamic measures (~6 muscles x 3 sequences x 4 lifts x 23 subjects), only one workload was analyzed. The 35 lb workload was used since it was expected to exhibit the highest amount of fatigue. For similar reasons, the lifting portion of the

CMMH activities was used to assess the dynamic fatigue of the study. This method of using the time history change in amplitude to assess dynamic fatigue of the muscles was modeled after a similar technique utilized in assessing the fatigue of the erector spinae muscles during lifting tasks at various percentage of maximal oxygen uptake (Petrofsky & Lind, 1978) and the assessment of the biceps brachii during fatiguing flexion-extension tasks (Potvin & Bent, 1997). Modifications to the methods in this study were made to address the limited duration of the trials and the inclusion of the additional trunk muscles.

All data collected were visually inspected and data identified as false or incomplete (such as a failure of the sensors to read or record due to technical difficulties) were excluded from further analysis. As a result, 15 EMG data sets of various muscles were excluded, or 5.7% of the collected data. Additionally, excessive signal noise was exhibited by both the LRA and RRA electrodes due to all subjects holding the boxes against the stomach (and electrodes) to account for the lack of handholds throughout numerous but various points of the lifting trials. This noise was not able to be discerned from the actual muscle activity for those sites and as a result that data was excluded from analysis, with the exception of the beginning and ending 75%MVC fatigue comparisons.

Data Analysis and Statistics

To evaluate the differences in the mean physiological responses between the three sequences with respect to the mean Normalized-EMG (%MVC) for each muscle for each sequence and workload within the sequence, the %Difference between the beginning N-MPF and ending N-MPF for each muscle for each sequence, and the N-EMG for the dynamic lifts of the 35 lb workloads for each muscle for each sequence, a paired Student's *t*-test was performed (listwise deletion used to account for missing subject data and data deleted due to technical issues). The data comparison between the Back-RPEs was performed using a Wilcoxon matched-pairs test (utilizing listwise deletion to account for missing subject trial data). GraphPad Prism 5.1 statistical software (GraphPad Software, La Jolla, CA) was used to conduct the statistical analysis. Significance level was set at $P < 0.05$. Results are reported as mean (SD).

Results

Muscle activity when sequence order is varied (by sequence)

The average Mean N-EMG results for each muscle are reported in Table 9. When the sequences were compared, there were significant differences in the activity of all the muscles between select pairs of sequences with the exception of the RBF muscle. The INC sequence was found to be significantly different than both the MIX and DEC sequences for all muscles with the exception of the LES muscle (where it was only significantly different from the MIX sequence). In these cases, the INC sequence consistently exhibited the lowest mean N-EMG as compared to both the other sequences. The DEC sequence was only found to be significantly different from the MIX sequence for the LES muscle but it exhibited the highest N-EMG in all instances where it was found to be significantly different from the other sequences.

Table 8
Mean N-EMG values for the left and right latissimus dorsi (LLD and RLD), erector spinae (LES and RES), and bicep femoris muscles (LBF and RBF) during the MIX, INC, and DEC sequences. Average of all subjects.

			MIX		INC		DEC
Mean N-EMG (%MVC)							
	LLD	*n=18*	**17.9 (13.1)**^{b*}	*n=20*	**13.3 (9.7)**^{a*,c}	*n=18*	**21.1 (18.2)**^{b}
	RLD	*n=19*	**15.3 (9.6)**^{b*}	*n=20*	**13.6 (15.3)**^{a*,c*}	*n=18*	**15.8 (10.7)**^{b*}
	LES	*n=18*	**46.0 (23.6)**^{b*,c}	*n=20*	**34.3 (16.8)**^{a*}	*n=18*	**53.2 (33.6)**^{a}
	RES	*n=18*	**45.3 (27.8)**^{b*}	*n=20*	**39.3 (27.7)**^{a*,c*}	*n=17*	**65.6 (50.1)**^{b*}
	LBF	*n=18*	**38.1 (21.1)**^{b*}	*n=18*	**24.4 (9.5)**^{a*,c*}	*n=18*	**34.9 (11.1)**^{b*}
	RBF	*n=19*	42.3 (31.6)	*n=19*	31.5 (18.6)	*n=16*	42.1 (20.3)

* ($p < 0.01$)
^{a} significantly different from MIX sequence ($p < 0.05$)
^{b} significantly different from INC sequence ($p < 0.05$)
^{c} significantly different from DEC sequence ($p < 0.05$)

Muscle activity when sequence order is varied (by workload)

The average Mean N-EMG values for each muscle within each workload of the sequences are shown in Figure 32 and the values are reported in Table 10. The level of significance between the INC sequence and the MIX sequence was met for all muscles with the exception of the LLD and RBF muscles in the 5 lb workloads; the LBF and RBF muscles in the 15 lb workloads; and the RBF muscles in both the 25 lb and 35 lb workloads ($p > 0.05$). Similarly, the INC sequence was significantly different from the DEC sequence for all muscles except the RES, LBF, and RBF muscles in the 5 lb workloads; and the LLD and RBF muscles in the 15 lb workloads ($p > 0.05$). There were no significant differences for any muscle in any workload between the MIX and DEC sequences. As with the sequence N-EMG means comparisons, the INC sequence, on average, exhibited the lowest mean amplitude regardless of muscle or workload and the DEC on average exhibited the highest for most of the muscles in every workload. This was visually evident in Figure 32. In terms of co-activity, it was apparent that as the weight increased the activity of all muscles increased as well, regardless of sequences order (Figure 32). For the DEC and MIX sequences, the RBF muscle appeared to be recruited more to aid the LES and RES muscles in handling the load.

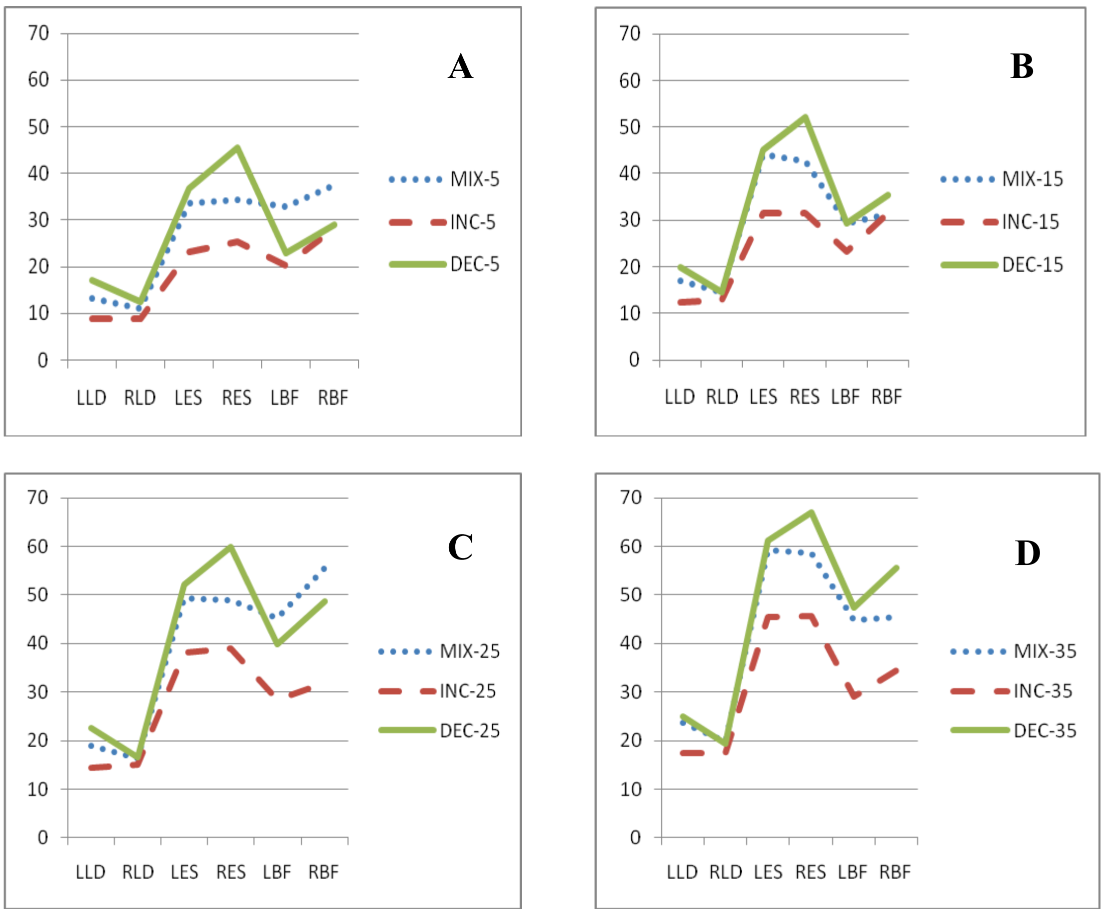


Figure 29: Mean N-EMG for the left and right latissimus dorsi (LLD and RLD), erector spinae (LES and RES), and bicep femoris muscles (LBF and RBF) during the MIX, INC, and DEC sequences: by workload A) 5 lb, B) 15 lb, C) 25 lb, and D) 35 lb. Average of all subjects.

Table 9

Mean N-EMG values for the left and right latissimus dorsi (LLD and LRD), erector spinae (LES and RES), and bicep femoris muscles (LBF and RBF) during the MIX, INC, and DEC sequences (by workload). Average of all subjects.

				MIX		INC		DEC
Mean N-EMG (%MVC)								
	5 lb	LLD	*n=19*	13.3 (10.0)	*n=20*	**8.8 (6.0)**[c]	*n=17*	**17.0 (18.1)**[b]
		RLD	*n=20*	**11.0 (7.3)**[b*]	*n=20*	**8.8 (8.9)**[a*,c*]	*n=17*	**12.5 (9.0)**[b*]
		LES	*n=19*	**33.7 (21.5)**[b]	*n=20*	**23.2 (12.1)**[a,c]	*n=17*	**36.8 (23.4)**[b]
		RES	*n=18*	34.4 (28.2)	*n=20*	**25.3 (18.1)**[c]	*n=17*	**45.5 (29.5)**[b]
		LBF	*n=19*	**33.0 (23.4)**[b]	*n=20*	**20.2 (10.5)**[a]	*n=18*	22.9 (8.1)
		RBF	*n=20*	**37.5 (37.9)**	*n=20*	**28.2 (19.4)**	*n=16*	28.9 (15.8)
	15 lb	LLD	*n=19*	**16.9 (12.4)**[b]	*n=20*	**12.4 (9.6)**[a,c*]	*n=17*	**19.8 (18.3)**[b*]
		RLD	*n=20*	**14.6 (9.2)**[b*]	*n=20*	**12.9 (16.0)**[a*]	*n=17*	14.6 (10.3)
		LES	*n=19*	**44.0 (22.9)**[b*]	*n=20*	**31.5 (15.9)**[a*]	*n=17*	45.1 (26.5)
		RES	*n=18*	**42.6 (27.3)**[b]	*n=20*	**31.6 (20.3)**[a,c]	*n=17*	**52.5 (33.0)**[b]
		LBF	*n=18*	29.3 (14.8)	*n=20*	23.2 (9.4)	*n=18*	29.4 (8.9)
		RBF	*n=20*	31.3 (20.3)	*n=20*	31.4 (19.2)	*n=16*	35.5 (16.2)
	25 lb	LLD	*n=19*	**19.0 (13.6)**[b*]	*n=20*	**14.5 (10.5)**[a*,c]	*n=17*	**22.7 (19.6)**[b]
		RLD	*n=20*	**16.3 (10.4)**[b*]	*n=20*	**15.1 (18.9)**[a*,c*]	*n=17*	**16.6 (12.1)**[b*]
		LES	*n=19*	**49.3 (25.8)**[b*]	*n=20*	**38.2 (18.9)**[a*,c]	*n=17*	**52.2 (32.5)**[b]
		RES	*n=18*	**48.9 (28.4)**[b*]	*n=20*	**39.1 (24.9)**[a*,c]	*n=17*	**60.0 (37.8)**[b]
		LBF	*n=19*	**45.2 (30.3)**[b]	*n=19*	**28.4 (9.3)**[a,]	*n=18*	39.9 (15.9)
		RBF	*n=20*	55.5 (55.8)	*n=19*	31.9 (18.9)	*n=17*	48.7 (27.5)
	35 lb	LLD	*n=19*	**23.7 (18.4)**[b]	*n=20*	**17.5 (13.2)**[a,c*]	*n=17*	**24.9 (18.2)**[b*]
		RLD	*n=20*	**19.8 (12.6)**[b*]	*n=20*	**17.5 (17.7)**[a*,c*]	*n=17*	**19.4 (11.7)**[b*]
		LES	*n=19*	**59.3 (31.1)**[b*]	*n=20*	**45.5 (22.5)**[a*,c]	*n=17*	**61.1 (35.7)**[b]
		RES	*n=18*	**58.6 (38.8)**[b]	*n=20*	**45.7 (27.9)**[a,c]	*n=17*	**67.1 (41.2)**[b]
		LBF	*n=18*	**44.8 (22.4)**[b*]	*n=19*	**29.1 (12.0)**[a*]	*n=18*	47.3 (18.0)
		RBF	*n=20*	45.4 (26.4)	*n=19*	**34.4 (19.3)**[c*]	*n=17*	**55.3 (26.0)**[b*]

[*] ($p < 0.01$)
[a] significantly different from MIX sequence ($p < 0.05$)
[b] significantly different from INC sequence ($p < 0.05$)
[c] significantly different from DEC sequence ($p < 0.05$)

Muscle fatigue (static)

The results for the % Difference in beginning and ending N-MPF are reported in Table 11. No significant differences were found between the sequences for any muscle with the exception of the RRA in the MIX sequence compared to the INC sequence (p = 0.0010). In this case, when the averages were evaluated, the INC sequence showed a decreased level of fatigue (i.e., the beginning N-MPF was higher than the ending N-MPF) whereas the MIX showed an increase in fatigue, which was expected [MIX: 23.6 (41.2)% *vs.* INC: -17.3 (42.6)%]. Also interesting to note, the LBF and RBF for all sequences showed a decrease in fatigue as well.

Table 10
Mean % difference between beginning N-MPF and ending N-MPF for the left and right latissimus dorsi, erector spinae, and bicep femoris muscles during the MIX, INC, and DEC sequences. Average of all subjects.

		MIX		INC		DEC	
N-MPF %Diff (%MVC-Intercept)							
	LRA	*n=20*	2.8 (28.1)	*n=20*	3.8 (41.9)	*n=19*	22.7(39.6)
	RRA	*n=20*	**23.6 (41.2)**[b*]	*n=21*	**-17.3 (42.6)**[a*]	*n=19*	17.6(45.4)
	LLD	*n=19*	6.0 (13.8)	*n=20*	5.5 (15.7)	*n=18*	0.0(11.3)
	RLD	*n=20*	3.0 (12.2)	*n=20*	1.4 (11.8)	*n=18*	7.4(16.7)
	LES	*n=20*	12.0 (16.5)	*n=21*	9.4 (12.2)	*n=18*	2.7(11.7)
	RES	*n=19*	4.3 (16.4)	*n=20*	9.5 (12.8)	*n=19*	9.8(13.6)
	LBF	*n=20*	-10.2 (22.0)	*n=20*	-5.5 (14.0)	*n=19*	-4.2(16.0)
	RBF	*n=17*	-8.1 (19.3)	*n=16*	-5.5 (17.8)	*n=17*	-5.0(28.5)

[*] ($p < 0.01$)
[a] significantly different from MIX sequence ($p < 0.05$)

[b] significantly different from INC sequence ($p < 0.05$)
[c] significantly different from DEC sequence ($p < 0.05$)

Muscle fatigue (dynamic)

The results of the *t*-test analysis indicated that there were no significant difference between the sequences with respect to the rate of change of the mean Dynamic N-EMG (slope) for each muscle throughout the complete lifting cycle for the 35 lb workload ($p < 0.05$). These results are reported in Table 12. Interesting to note, almost every muscle showed a negative average slope from start of workload until the last lift. The only exceptions were the LES and RES muscles in the DEC sequence, where the mean muscle activity increased throughout the cycle.

Table 11
Mean Dynamic N-EMG Slope (%MVC) of each muscle for lifts occurring every 33% interval for the duration of the 35 lb workload (3 minutes) in the MIX, INC, and DEC sequences. Average of all subjects.

			MIX		INC		DEC
Mean Dynamic N-EMG Slope (%MVC)							
	LLD	*n=18*	-2.1 (6.7)	*n=21*	-1.3 (5.2)	*n=17*	-1.5 (5.1)
	RLD	*n=18*	-1.3 (4.4)	*n=20*	-1.0 (5.3)	*n=18*	-1.9 (3.8)
	LES	*n=18*	-4.4 (11.2)	*n=20*	3.0 (15.3)	*n=18*	5.5 (10)
	RES	*n=18*	-7.0 (28.0)	*n=20*	-1.4 (10.5)	*n=17*	2.5 (16.0)
	LBF	*n=18*	-10.0 (18.1)	*n=19*	-0.5 (10.3)	*n=18*	-6.4 (18.7)
	RBF	*n=19*	-8.5 (15.0)	*n=19*	-1.4 (8.9)	*n=16*	-3.3 (37.5)

No significant differences were found
Level of significance ($p = 0.05$)

As with the N-EMG Amplitude for the 35 lb workloads, the *t*-test analysis indicated that there were no significant differences between the sequences with respect to the mean Dynamic N-EMG (at start of lift) of any muscle during lifts occurring at 0, 33, 66, and 100% of the cycle for the 35 lb workload. These EMG amplitudes were normalized by using the first lift ('@ 0% of cycle') as the basis to account for any inter-subject differences. The trends throughout the lifting trials for each muscle are shown in Figures 33 – 38. For the RLD (Figure 34), the INC sequence consistently produced a higher mean Dynamic N-EMG as compared to both the MIX and DEC sequences. For the LES, RES, and LBF muscles (Figs 35, 36, and 37), the DEC exhibited the higher Dynamic N-EMG throughout the course of the cycle for these muscles. However, these differences are deemed insignificant due to the relatively high standard deviations.

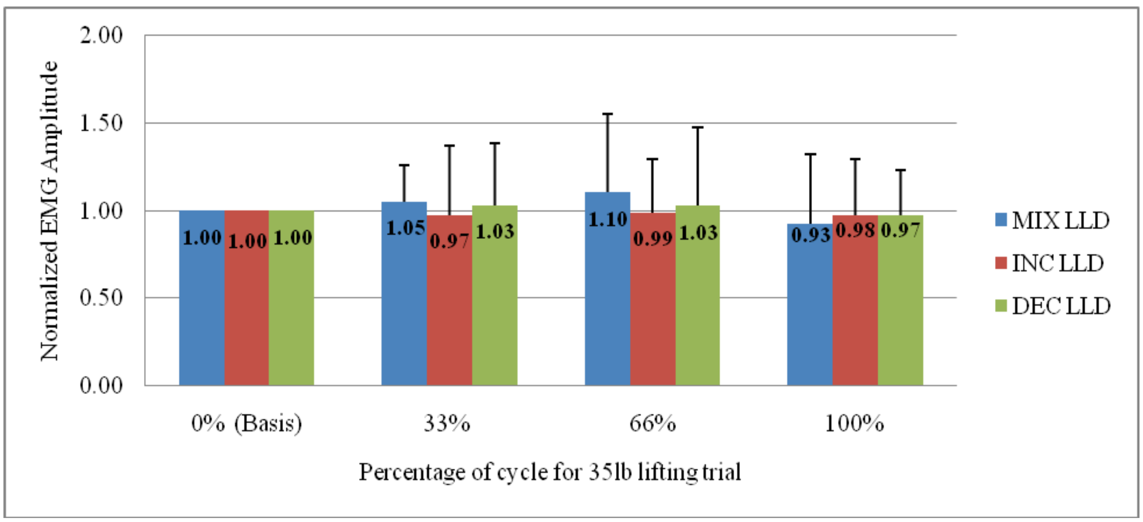


Figure 30: Mean Dynamic N-EMG for the left latissimus dorsi (LLD) muscle for the 35 lb workload at each 33% interval of the workload cycle in the MIX, INC and DEC sequences. Average of all subjects. Values calculated as a percentage of the average peak EMG amplitude at the start of the first lift (@ 0% of cycle). Error bars are SD.

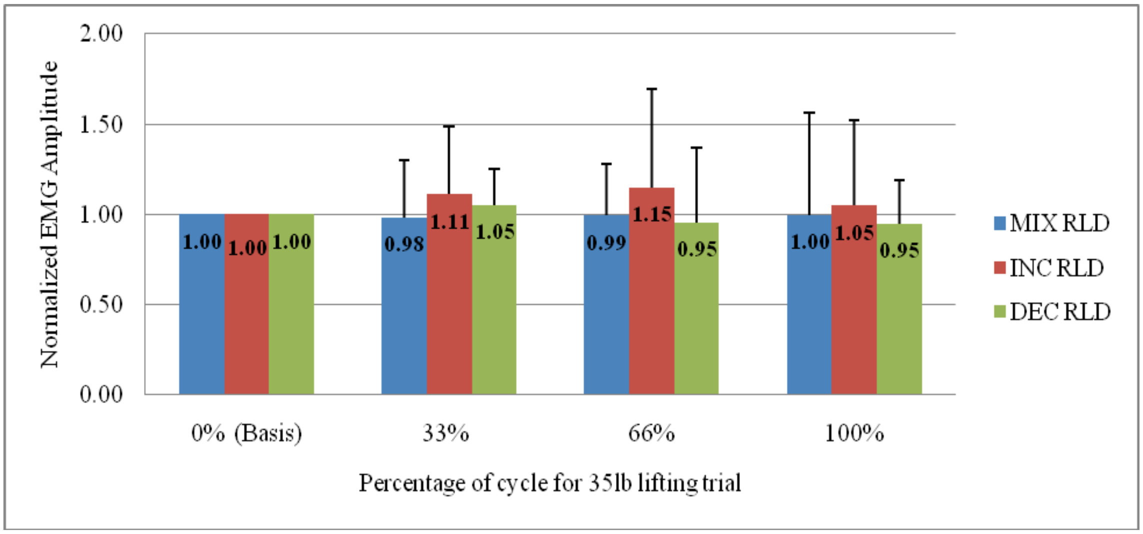


Figure 31: Mean Dynamic N-EMG for the right latissimus dorsi (RLD) muscle for the 35 lb workload at each 33% interval of the workload cycle in the MIX, INC and DEC sequences. Average of all subjects. Values calculated as a percentage of the average peak EMG amplitude at the start of the first lift (@ 0% of cycle). Error bars are SD.

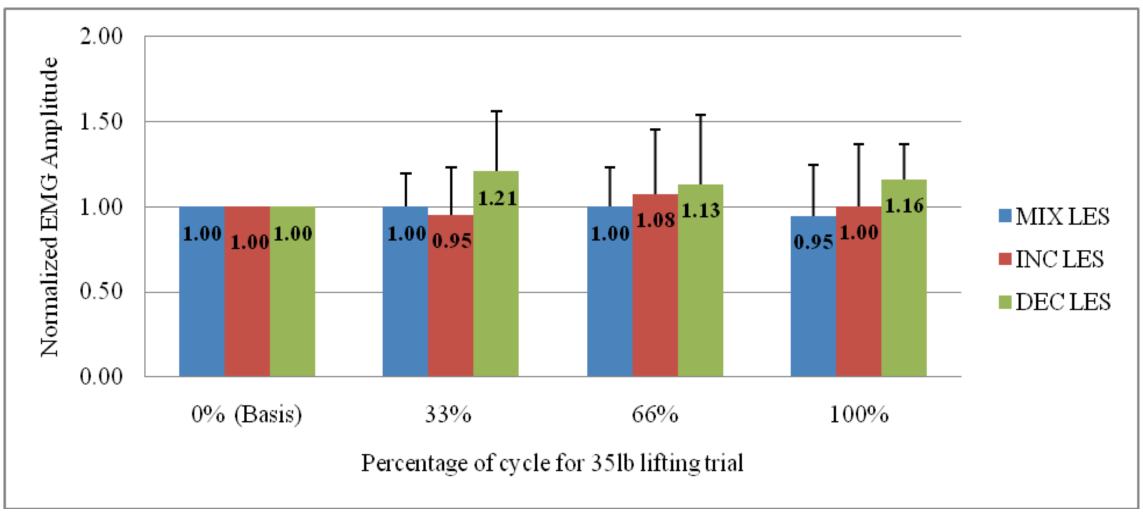


Figure 32: Mean Dynamic N-EMG for the left erector spinae muscle (LES) for the 35 lb workload at each 33% interval of the workload cycle in the MIX, INC and DEC sequences. Average of all subjects. Values calculated as a percentage of the average peak EMG amplitude at the start of the first lift (@ 0% of cycle). Error bars are SD.

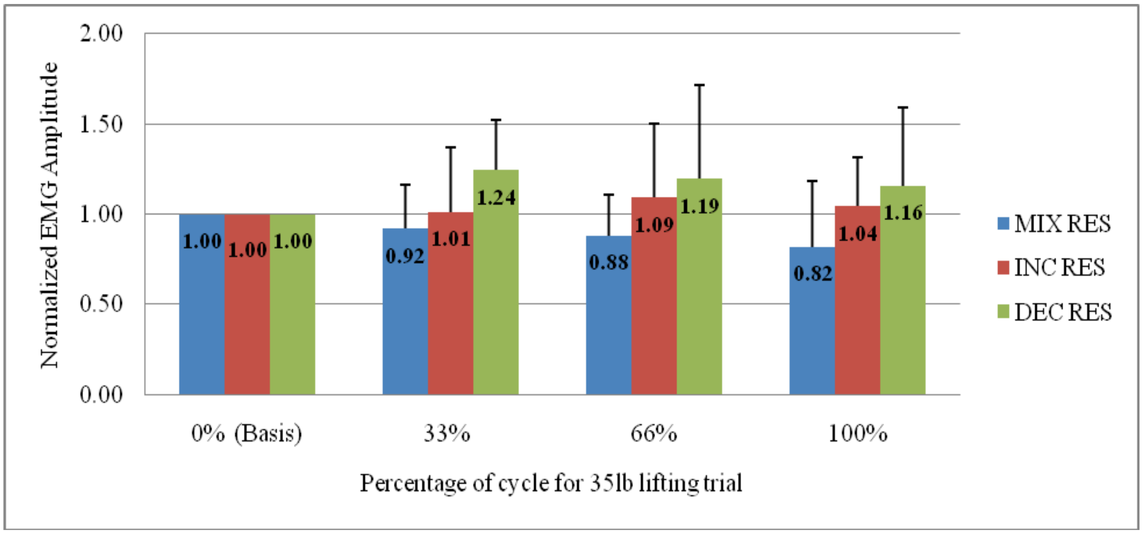


Figure 33: Mean Dynamic N-EMG for the right erector spinae muscle (RES) for the 35 lb workload at each 33% interval of the workload cycle in the MIX, INC and DEC sequences. Average of all subjects. Values calculated as a percentage of the average peak EMG amplitude at the start of the first lift (@ 0% of cycle). Error bars are SD.

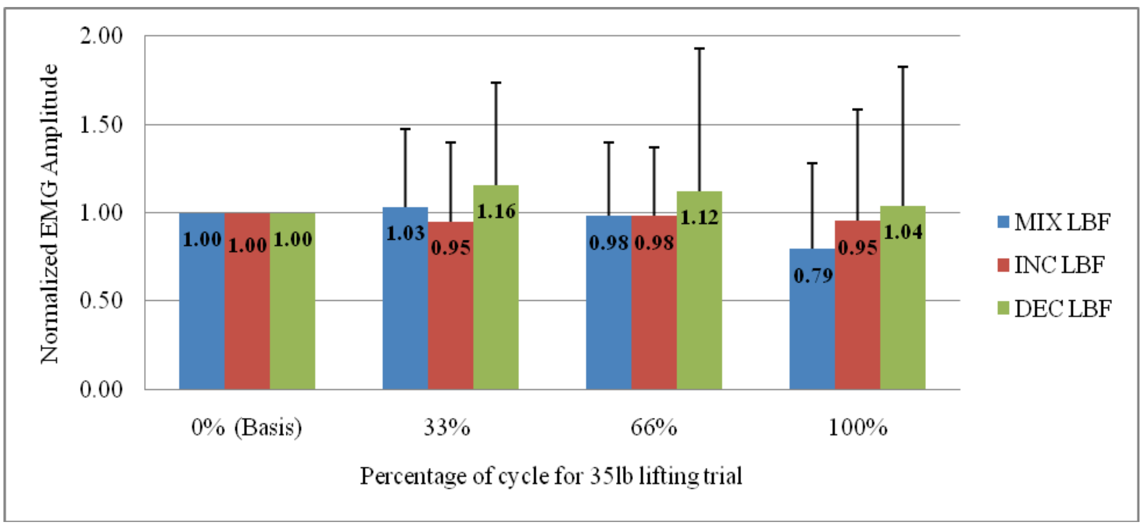


Figure 34: Mean Dynamic N-EMG for the left bicep femoris muscle (LBF) for the 35 lb workload at each 33% interval of the workload cycle in the MIX, INC and DEC sequences. Average of all subjects. Values calculated as a percentage of the average peak EMG amplitude at the start of the first lift (@ 0% of cycle). Error bars are SD.

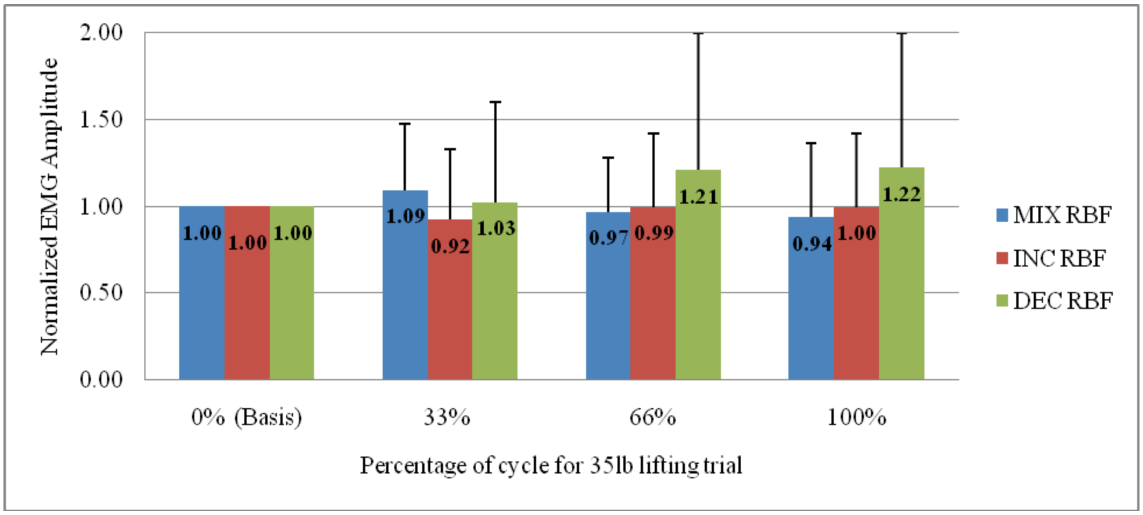
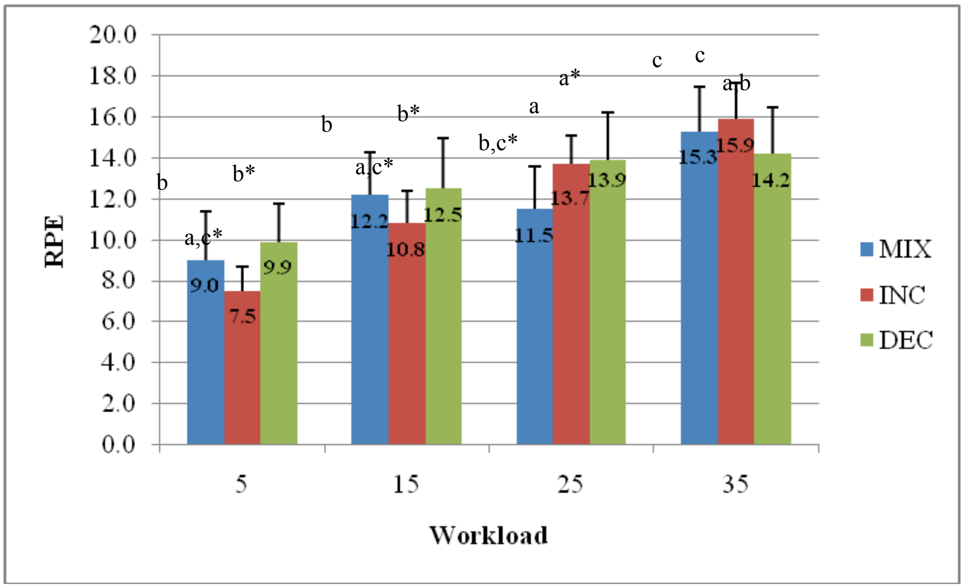


Figure 35: Mean Dynamic N-EMG for the right bicep femoris muscle (RBF) for the 35 lb workload at each 33% interval of the workload cycle in the MIX, INC and DEC sequences. Average of all subjects. Values calculated as a percentage of the average peak EMG amplitude at the start of the first lift (@ 0% of cycle). Error bars are SD.

Back-RPE

Several significant differences were found between the workloads across the sequences with respect to Back-RPE (Figure 39). The 5 lb workload in the MIX and DEC sequence was found to be, on average, 20% and 32% more exerting than the INC sequence, respectively [MIX: 9.0 (2.4) *vs.* INC: 7.5 (1.2) and DEC: 9.9 (1.9) *vs.* INC: 7.5 (1.2)]. In these comparisons, the differences were found to be significant (p = 0.0104 and p = 0.0010, respectively). For the 15 lb workload, the DEC sequence was found to be more exerting, by 16%, when compared to the workload in the INC sequence [DEC: 12.5 (2.5) *vs.* INC: 10.8 (1.6)] and in the MIX it was 13% more exerting than in the INC sequence [MIX: 12.2 (2.0) *vs.* INC: 10.8 (1.6)]. As before, these comparisons were found to be significantly different (p = 0.0033 and p = 0.0185, respectively). Both the INC and DEC sequence were more exerting, on average, than the MIX sequence for the 25 lb workload (p = 0.0330 and p = 0.0037, respectively)

[INC: 13.7 (1.4) *vs.* MIX: 11.5 (2.1) and DEC: 13.9 (2.3) *vs.* MIX: 11.5 (2.1)]. With the 35 lb workload, both the MIX and INC sequence were more exerting than the DEC sequence ($p = 0.0144$ and $p = 0.0123$, respectively) [MIX: 15.3 (2.7) *vs.* DEC: 14.2 (2.2) and INC: 15.9 (1.7) *vs.* DEC: 14.2 (2.2)].



* ($p < 0.01$)
[a] significantly different from MIX sequence ($p < 0.05$)
[b] significantly different from INC sequence ($p < 0.05$)
[c] significantly different from DEC sequence ($p < 0.05$)

Figure 36: Back-RPE for each workload in each sequence. Average of all subjects. Error bars are SD.

Discussion

The overall aim of this study was to determine if varying the sequence of the workload would have a significant impact on the fatigue development and/or activity on trunk muscles while performing a simulated order picking task. The sequences in this study only differed in work ordering, thus only the ordering was evaluated as the independent variable. The results for this study as it pertains to the various dependent variables were mixed with some showing significant differences between the sequences orders while others did not. When the sequences as a whole were evaluated, only select sequence comparisons were shown to be significantly different for various muscles. The RBF muscle exhibited no significant difference between any sequence orders. However, a majority of the muscles exhibited a significant difference in the INC sequence when it was compared to either the MIX or DEC sequence. In these cases, the INC sequence (5-15-25-35) on average consistently exhibited a lower amount of muscle activity. The reason why the INC sequence would elicit lower levels of muscle activity than other sequence orders is unclear considering most of the research, albeit limited, evaluating alternative exercise/work patterns revolves around cardiopulmonary responses (Björklund, Pettersson, and Schagatay, 2007). It is, however, speculated that starting with a higher workload initially enlists higher amounts of muscle activity and as the sequence progresses these levels remain high due to the higher initial degree of muscle fatigue. For example, in the INC sequence, the sequence begins with the lowest workload and then increases throughout. In the higher DEC sequence, the beginning workload was relatively high. Despite consistently decreasing to a lower workload, as was the case for the DEC sequence, the average level of LES muscle activity (for example) for the entire sequence was, on average, considerably higher than the INC sequence (53.2% vs. 34.3%). This seemed to be further evident when the muscle activity for each workload was evaluated (Figure 32). For example, for the 5 lb workload in the INC sequence where the workload was the starting workload, the average Mean Normalized-EMG for the RES muscle was 25.3%. This was lower than the amount of EMG activity seen for the same workload in the MIX sequence (34.3%), where the workload followed a higher intensity workload. Similarly, the RES muscle for the 15 lb workload in the INC sequence exhibited less activity than the DEC sequence. This was further supported by the subjects' perceived exertion as represented by similar results in Back-RPE for the workloads. From the results of the present study, it appears as though muscle activity was dependent not on the extent of the weight of the load but rather on the load's location within the sequence order. Here, muscle activity for some muscles varied significantly when the preceding workloads altered between intensities; with higher preceding intensities eliciting a higher level of activity. Given that not all muscles exhibited statistically significant differences in this present study (e.g. the RBF muscles), the above speculation would have to be expanded to include that the significant changes in muscle activity levels are selective. This further suggests that there may be a specific dose-response relationship with regards to the recruitment activity of the various trunk muscles in various sequence patterns; one that was not determined within this study. It has been shown that there is an increased amount of muscle activity as well as co-activity of the trunk muscles as weight increases during lifting tasks (Davis and Marras, 2000; Gallagher, Marras, Davis, and Kovacs, 2002; Marras, Davis, and Jorgensen, 2003). As seen in these previous studies, the uptick in activity and recruitment of the other trunk muscles observed in this study could have been a means to compensate for the increased weight and/or accumulating fatigue. An increase in muscle activity is a sign of increased loading on the spine (Chaffin & Andersson, 1991) and an increase in trunk muscle recruitment has been reported to negatively influence the moments and forces applied to the lumbar spine (Gallagher, 2002). Therefore, higher yielding co-activity sequences may also reflect situations where the loading makes it necessary to recruit additional muscles in order to protect the stability of the spine to handle the increased loads. With that, effort would be warranted to minimize such situations through effective sequence ordering, particularly those cases where the work is such that the spine's stability requires more protection. However, research has shown that it is the recruitment and increased activity of the abdominal and latissimus dorsi muscles that mostly signifies this type of spinal jeopardy (Cholewicki & McGill, 1996) due to their influence on the shear force applied to the spinal column (Granata & Marras, 1995) because of their oblique orientation to the spine (Marras, Jorgensen, Granata, & Winand, 2000). Unfortunately, the responses of the LRA and RRA muscles as it pertains to their activity throughout the course of the dynamic portion of this study were unable to be definitively ascertained due to the 'on the stomach' handling of the boxes which were not equipped with hand holds. Oblique muscles were not evaluated during this study because the CMMH activities were designed to be symmetrical. Therefore no evaluation can be made about the sequence comparisons with regard to abdominal muscle activities. The activities of the LLD and RLD did vary between the sequences with the INC sequence consistently exhibiting significantly lower levels when compared to the MIX and DEC sequences (Table 9 and Figure 32). This would suggest that an increasing pattern as seen in the INC sequence would be preferred over a decreasing or varied pattern sequence to minimize muscle activity over time. However, given the limited scope of this study and the varying responses of the specific muscles with respect to the various sequence orders, further investigation into the impact workload variations in CMMH work has on trunk muscle activity is warranted before a definitive determination of sequence order preferences can be made.

Whereas changes in the muscle activity were found to be significant for some muscles in terms of overall sequence comparisons and for individual workloads, these changes did not translate into significant differences in the static EMG muscle fatigue index, with the exception of the RRA muscle in the MIX and INC sequences. Nor did the rate of fatigue during the lifting trial appear to be impacted by the 35 lb workload's position within the sequence as there were no significant differences in the dynamic N-EMG slope for any muscle as measured over the workload's cycle within the respective sequences. This was contrary to the observed increase of the EMG amplitude in the Petrofsky et al (1978) of the erector spinae muscles over time. It should be noted that the experiment was limited in duration by design, therefore longer durations or trials that take participants to the point of exhaustion may exhibit varied EMG responses; both within and between the sequences. Nevertheless, these fatigue measure results did not support the hypotheses that sequence order would alter overall sequence fatigue.

Another aspect of the present study was to determine if varying the sequence order to reflect an 'up/down' type of pattern would have any significant effects on muscle activity or fatigue. From the results of the study, it also appears that insertion of a lower workload in between two higher workloads as a means of 'active' recovery had no impact on localized muscle activity or perceived exertion. The 35 lb workload in the MIX sequence, which was preceded by the 5 lb workload, showed more muscle activity than the INC sequence, on average (with the exception of the RBF which was found to not be significantly different). This is highly interesting considering the 35 lb workload was positioned last in the latter sequence. Furthermore, the Back-RPE for the 35 lb workload in the MIX sequence was not found to be significantly different from the INC sequence (15.3 *vs.* 15.9, respectively). Because the MIX sequence did not fare better than the other sequences (and at times performed worse in terms of increased activity, on average) this would suggest that 'active' recovery schemes utilized in cardiopulmonary focused methods as a means to mitigate whole-body fatigue and enhance performance does not afford the same benefits to the localized trunk muscle fatigue.

In interpreting the results, limitations of the study should be considered. Although the experiment was designed to represent real world order picking, not all characteristics were included. The weights in this study were chosen because they reflected ~97% of the carton weights determined from a substantial sampling (N= 865 cartons) of data from the Big Lots Distribution Center. However, order pickers can be expected to handle loads up to 70lbs. Furthermore, the cartons picked vary significantly in terms of size, shape, and condition. The boxes in this study were controlled in shape and size (16" x 12.5" x 12.5"). Average picks at the distribution center (i.e., 'sequence') have a duration of ~60 minutes and the individual picks can range from a few seconds to several minutes as dependent on the quantity required for each outbound product. Due to the objectives of this investigation the duration of the individual workloads (3 minutes), and thus the sequence, was limited in this study. Given the possibilities of weight, package size and shape, and pick durations, it would be infeasible to include all potential sequence combinations. Therefore, only three sequence patterns were included in this study in an effort to reflect an increasing, decreasing, and mixed pattern for early comparisons in a research area that has been uncharted. There were potential limitations to the execution of the study as well. One such potential concern was the conformity of the lifting and lowering postures of all the subjects throughout all trials. Although effort was made to ensure subjects conformed to the semi-squat posture throughout the study by means of verbal encouragement on part of the investigator, it was possible that lifting techniques were varied at points throughout the study. This variation in lifting could have impacted the extent of the individual or group muscle activities and/or fatigue responses as posture has been shown to alter trunk muscle recruitment in lifting tasks (Gallagher et al., 2002). Although it was not observed to be extensive, there was the potential for the subjects to twist with the load after the lift from both the pallet and table despite instructions to the contrary. It was observed that the majority of the subjects opted to use a counter-clockwise, or to the left, route to and from the table even though it was not instructed. This route possibly coupled with an asymmetrical lift/lower could have impacted the EMG readings of the LES, LBF, and possibly the LLD. However, this counter-clockwise route and the potential for twisting were observed for all three sequences; thus it would not explain any of the significant differences seen with these muscles between the sequences. Another potential limitation was the reporting of the Back-RPE. The subjects were aware of the specific weight they were lifting at all times and therefore their subjective responses could have been biased by this knowledge. Knowing the package weight is a realistic expectation in a real work scenario. Finally, the characteristics of the subjects were a potential limitation. Both young men and women participated in the study. Due to the high standard deviations, it was suspected that gender may be a confounding factor, because it has been shown that women can exhibit significantly higher levels of peak trunk muscle activity characteristics in lifting tasks when compared to their male counterparts (Marras et al., 2003). Given that the workloads in this experiment were fixed (i.e., the weights were the same for each participant as opposed to a set percentage of their MVC), it was plausible that similar differences could have been seen in this present study, and thus possibly accounting for the relatively high standard deviations seen throughout. Even though the differences between the performances of the genders were not tested comprehensively, a post-hoc evaluation of a subset of the data suggested that there was no evidence of significant differences. For example, the evaluation of the mean N-EMG for the sequences showed that the average difference between men and women for all muscles included in the study analysis was only 6.4%, 9.7%, and 6.4%, for the MIX, INC, and DEC sequences, respectively. Furthermore, statistical data analysis showed that there were no significant differences between the male and female participants for N-EMG sequence means for the various muscles either ($p > 0.05$). Therefore, it appears as though gender differences were not at play within this study. However, there could have been other differences within the subject population that could have impacted the results, which again were normalized specifically to the participants MVC. One such difference could be the physical fitness of the individual participants. MMH encompasses all facets of physical capabilities, including cardio fitness as well as relative upper and lower body strength. Given the population, it was highly feasible that the participants would have a relatively non-sedentary lifestyle, but no screening criteria for specific physical capabilities were included in the recruitment portion of this study. Furthermore, weights lifted were consistent for each subject (5 lb – 35 lb) as opposed to varying the weights for the subjects relative to specific intensities which are expected to significantly fluctuate due to individual fitness levels. So it is possible that participants could have varied significantly in these characteristics.

Conclusion

The overall aim of this study was to determine if varying the sequence of the workload would have a significant impact on the fatigue development or activity on trunk muscles while performing a simulated order picking task. The goal was to ultimately add to manual material handling research in an effort to aid in minimizing the occurrence of MSDs, particularly those of the back. Given there were a considerable number of significant differences between the sequences for the various muscles, the results of the present study do suggest that sequence order does significantly impact various physiological responses and it has the potential to do so under other realistic CMMH conditions. However, with the mixed results amongst the muscles within the sequences and workloads in terms of which sequence consistently exhibited a higher or lower result, it would be premature to assert one sequence pattern as superior to others as a potential means to reduce the occurrence of these MSDs. Therefore additional research is needed to better understand these responses which are very important to the goal of minimizing injuries in these types of jobs.

CHAPTER SIX

SUMMARY: RESEARCH CONTRIBUTION AND PROPOSED SUGGESTIONS FOR FUTURE RESEARCH

The occurrence of MSDs is an ongoing issue in the Manual Material Handling (MMH) industry. Despite the extensive amount of research that has been conducted in the area of material handling with the goal of controlling and minimizing these injuries, it is apparent that opportunities to add to this research exist. One method to address these injuries is through optimization of work with the objective to minimize fatigue. Finding the best order of work to minimize fatigue has long since been a goal of ergonomics and industrial engineering as seen from research focusing on job rotation and work/rest cycles and the application of fatigue allowances. Research has shown that fatigue, both whole-body and localized muscle fatigue, is an important factor that should be considered in the effort to minimize the occurrence of MSDs. One characteristic of MMH that has yet to be examined is the varying of workloads while performing combined manual material handling (CMMH) activities. CMMH with variations in the workloads are a common event in industry, but design guidelines and work measurement fail to incorporate these characteristics. In recent years, the discipline of Operations Research has expanded scheduling theories to include objectives to minimize injuries and maximize productivity through optimization of human tasks sequencing in operations such as order picking.

However, little is known about the impact work variation has on physiological responses that have been used to infer fatigue and used as a basis of designing work to control fatigue and subsequently injuries. Therefore, more understanding of these responses in this type of MMH work was warranted. The purpose of this body of research was to initiate the discussion on and begin investigations of these responses that account for this type of operation.

To address the research needs discussed above, this research was separated into three separate studies. The first study was designed as a starting point to begin investigation of the low intensity CMMH work including the workload variation. Because of the wide-spread use of the traditional physiological approach to MMH, objective heart rate and subjective perceived exertion related responses were evaluated to identify if any significant changes could be observed when workload orders were alternated in terms of preceding workloads and extended sequences. Alternating prior workload intensity and incorporating periods of 'active' work has been a method in exercise physiology as a means to improve exercise performance through reduced fatigue. The quest to determine the most effective workload combinations continues to fuel research in this area. However, this approach has not been addressed in low intensity CMMH work even though the stochastic characteristics in work patterns are similar. The intention of this study was to address this void. The study's findings suggested that alternating these low intensity workloads caused insignificant changes in these physiological responses. Thus it was concluded that efforts made to optimize work order in this specific type of low intensity work may not see significant benefits when these physiological responses were used as the measure.

The limitations of the first study's design led to the second study which sought to evaluate the same physiological responses plus energy expenditure, but in more fatiguing conditions and with additional sequence patterns. It also sought to expand knowledge about the applicability of commonly used energy prediction models that have failed to account for general CMMH activities as well as those activities that include workload variations. In this study the results suggest that lifting, lowering, carrying, pushing, and pulling boxes of varying weights in varying workload order did impact overall heart rate related measures for the sequences as a whole as well as significantly affecting heart rate kinetics of select workloads in select sequences but in different magnitudes. This suggested that there may be a specific dose-response relationship thus offering opportunities for optimization through sequence ordering. It also suggested that energy expended during the various sequence orders were not significantly different from each other or from the energy prediction models. However, recognized concerns about both methods highlighted that the use of energy expenditure monitors and prediction models in CMMH operations should be evaluated further.

The third study was designed to further investigate the impact of sequence ordering by evaluating the localized trunk muscle responses; a physiological measure that is limited in MMH research but has been shown to be a more significant contributor to MSDs as compared to traditionally used cardiopulmonary measures. This study sought to characterize through EMG the development of fatigue, activity, and recruitment patterns of eight trunk muscles in the CMMH activities identified in the second study. The results of this study suggested that activity of select muscles was significantly impacted by sequence order. Therefore, with additional research, optimization may be a viable mitigation method to reduce MSDs of the back. Furthermore, the study showed that the lack of a significant affect of sequence order on fatigue development as depicted through EMG spectral analysis suggested that muscle activity may be a more effective measure in determining the impact of varying sequence order.

Future Research

Considering the results of these studies and the high prevalence of MSDs of the back in the MMH industry, it is recommended that efforts be made through additional research to further examine the physiological responses, particularly the localized trunk muscle response, to various other workload sequence combinations and CMMH conditions to determine optimal sequencing patterns of this type of work.

Manual warehouse order picking was used as the reference for the experiment design in the above studies. Due to the complexity of the order picking task in terms of weight, package characteristics, duration, environment, and combinations thereof, it was impossible for the studies to answer all questions related to this type of CMMH work and offer a definitive recommendation for preferred sequence ordering. Thus, there are opportunities to gain a better understanding of how this work can be optimized in order to reduce the occurrence of injuries and increase productivity. The following are suggestions for future research as determined from the limitations of the present studies:

- It was impossible for the three studies in this body of work to evaluate all the different combinations of workload sequences and fully assess the impact varying sequence order would have physical responses. There exists opportunity for future research to examine other combinations in terms or workloads and durations of sequences and further expand the concept of active recovery/work and interval training for CMMH work.

- In all three present studies, the environment with regards to temperature was controlled as much as possible (68.9°F to 71.6°F). However, the work in the Big Lots Distribution Center in Montgomery, AL in the month of July was observed to be significantly hotter. In addition, high humidity in the facility was an issue as well. Fatigue has been shown to be relative to environmental factors such as temperature and humidity levels (Gonzalez-Alonso, Grandall, & Johnson, 2008; Neilsen, Savard, Richter, Hardgreaves, & Saltin, 1990). It is recommended that environmental factors, such as exposure to heat, cold, and/or humidity, be examined in this CMMH activity.

- Trunk muscle activity has been shown to be affected by posture (Gallagher , Marras, Davis, & Kovacs, 2003). For the first study of this present work, participants remained in an 'upright' or standing posture. In the second and third studies, the participants repeatedly lifted and lowered boxes in a semi-squat posture (Chen, Yang, Ding, & Wang, 2004). Considering that order pickers pick boxes from various locations on the pallet including extended reaches to the far side of the pallet, it is recommended that extended reach postures be examined in conjunction with and/or separately from the before mentioned postures.

- Per the design of the experiments, the handling durations were controlled. However, workload variations in the most realistic order picking assignments are stochastic in nature with respect to duration of the pick. Research has not been shown to address this type of non-steady work and it is unclear how extremely short durations coupled with changes in weight would impact the various physiological and psychophysical measures. Therefore it is suggested that future research be designed to encompass evaluations of this characteristic of CMMH work.

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Appendix 3-A

RECRUITMENT SCRIPT

My name is Bobbie Watts, a graduate student in the Department of Industrial and Systems Engineering at Auburn University. I would like to invite you to participate in a research study to evaluate the physiological effects of warehouse order picking. You may participate if you are between the ages of 19 and 65 and are currently enrolled in INSY 3021 (Sp '08). Please do not participate if you are pregnant, currently have a musculoskeletal injury, or under any type of work and/or exercise medical restriction.

As a participant, you will be asked to pick and place packages of various weights (from 5 to 35 lbs) at a set work pace while wearing a heart rate transmitter. You will pick the packages in various sequences until you are asked to stop. The total time commitment, including equipment applying and removal and rest breaks, is expected to be at least one hour but no more than two hours.

There is a slight risk of whole body and/or localized muscle fatigue from lifting the packages, and a risk for an acute injury from a dropped package. There is also the risk of minor discomfort from wearing the heart rate transmitter, but that is expected to be minimal. All information collected will be confidential and the data will be coded only as a link for data analysis. There will be no compensation for participating in this experiment, however, extra credit will be offered as part of INSY 3021 Lab. Any one choosing not to participate will not be penalized in any way. Those who chose to participate but are excluded per the restrictions of the study will be given an alternate assignment to complete for equivalent extra credit.

If you would like to participate in this research study, please contact me at wattsbj@auburn.edu.

Do you have any questions now? If you have questions later, please contact me at my email address above or you may contact my advisor, Dr. Davis, at davisga@auburn.edu.

Appendix 3-B

Auburn University

Auburn University, Alabama 36849-5346

Samuel Ginn College of Engineering

Department of **Telephone: (334) 844-1411**

Industrial and Systems Engineering **Fax: (334) 844-1381**

3321 Shelby Center

INFORMED CONSENT
for a Research Study Entitled
Sequencing human tasks: a new paradigm for scheduling research – PART II

You are invited to participate in a research study that seeks to determine physiological responses to the workloads associated with various tasks performed during order picking. This study is being conducted by Dr. Jerry Davis, Assistant Professor of Industrial and Systems Engineering. We hope to learn if sequencing the picks by workload provides any physiological benefit to workers engaged in these activities. There is a small risk for injury (whole body and/or localized muscle fatigue from lifting packages or acute injury from a dropped package). If this occurs, you will be responsible for any and all medical treatment if it is sought. All data collected will be anonymous and confidential.

Participation in this study is completely voluntary. If you decide to participate, we will ask you to wear a heart rate monitor (similar to those worn by runners), simulate material handling picking scenarios, and answer a couple of short questions after each simulated pick. We intend to have you wear the monitor and simulate picking for approximately one hour. There is a small possibility that you might feel some slight discomfort when you first put on the heart rate monitor until you become familiar with wearing it.

You will not receive any direct benefit from participating in this research other than a lab grade for participation. We will use this data to develop physiological constraints for order picking scheduling models.

Any information obtained in connection with this study and that can be identified with you will remain anonymous. Information collected through your participation may be used to fulfill educational requirements, published in a professional journal, and/or presented at a professional meeting. If so, no identifiable information will be included.

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Participant's Initials
Page 1 of 2

You may withdraw from participation at any time, without penalty, but since any data collected on you is unidentifiable, it will not be able to be withdrawn. Your decision whether or not to participate will not jeopardize your future relations with Auburn University or the Department of Industrial and Systems Engineering.

If you have any questions we invite you to ask them now. If you have questions later, please feel free to contact Dr. Jerry Davis at (334) 844-1411, or at davisga@auburn.edu, and he will be happy to answer them for you. You will be provided a copy of this form to keep.

For more information regarding your rights as a research participant you may contact the Auburn University Office of Human Subjects Research or the Institutional Review Board by phone (334)-844-5966 or e-mail at hsubjec@auburn.edu or IRBChair@auburn.edu.

HAVING READ THE INFORMATION PROVIDED, YOU MUST DECIDE WHETHER OR NOT YOU WISH TO PARTICIPATE IN THIS RESEARCH STUDY. YOUR SIGNATURE INDICATES YOUR WILLINGNESS TO PARTICIPATE.

Participant's signature	Date	Investigator obtaining consent	Date
Print Name		Print Name	

Appendix 3-C

Material Handling Work Physiology Study Pre-Participation Screening
(Adapted from the Health & Fitness Pre-Participation Screening Questionnaire AHA / ACSM, 1998 & Risk Stratification ACSM, 2000)

Date: ____________________ **Ht (in):** ____________________

Age: ____________________ **Wt (lb):** ____________________

Gender: ____________________

Assess your health needs by marking true statements

History

You have had:

______	Cardiac Catheterization	______	Congenital Heart Disease
______	Coronary Angioplasty (PCTA)	______	Heart Attack
______	Heart Failure	______	Heart Surgery
______	Heart Transplantion	______	Heart Valve Disease
______	Pacemaker / Implantable Cardiac Defibrillator / Rhythm Disturbance		

Signs / Symptoms

You have had:

______ You experience chest discomfort with exertion

______ You experience unreasonable breathlessness

______ You experience dissiness, fainting, blackouts

______ You experience swelling at the ankles

______ You have a known heart murmur

______ You take heart medications

Other Health Issues

______ You have back pain / injury

______ You have joint pain / injury (knees, elbows)

______ You are pregnant

Cardiovascular Risk Factors

_______ Family history of heart disease: male family member before age 55; female family member before age 65

_______ Cigarette Smoker: current or have quit within last 6 months

Continue on next page

_______ High Blood Pressure: SBP $\geq$ 140 or DBP $\geq$ 90 OR on medication to control

_______ High Cholesterol: Total > 200 or HDL < 35 or LDL > 130 OR on medication to control

_______ (-) HDL > 60

_______ Diabetes (Type I or Type II) OR on medication to control

_______ Obesity: BMI > 30 or waist > 39in

_______ Sedentary Lifestyle (less than 30 min of physical activity per day)

Do not write in this section

Risk Stratification

_______	LOW	(males age < 45; females < 55 with no signs/symptoms and $\leq$ 1 risk factor)
_______	MODERATE	(males age $\geq$ 45; females $\geq$ 55 with no signs/symptoms and $\geq$ 2 risk factor)
_______	HIGH	($\geq$1 sign/symptom OR known cardiovascular, pulmonary, or metabolic disease)

Code:

Appendix 3-D

Material Handling Work Physiology Study - Part II: Data Collection Sheet

Participant #:	____________		Age:	_______	Resting HR ___
Date:	_____		Predicted HRmax:	_______	
Time:	_____		85% HRReserve:	_______	
		Ht (in) _____	Wt (lb)	_______	
Seq #					

Weight ___		Weight ___		Weight ___		Weight ___		Recovery	
30s		30s		30s		30s		20s	
1		1		1		1		1	
1.5		1.5		1.5		1.5		1.5	
2		2		2		2		2	
3		3		3		3		2.5	
4		4		4		4		3	
5		5		5		5		3.5	
6		6		6		6		4	
7		7		7		7		4.5	
8		8		8		8		5	
								7	
								7.5	
						RPE		8	
								8.5	
								9	
								9.5	
								10	

Comments ______________________________

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Appendix 4-A

Auburn University

Auburn University, Alabama 36849-5346

Samuel Ginn College of Engineering

Department of **Telephone: (334) 844-1424**
Industrial and Systems Engineering **Fax: (334) 844-1381**
3310 Shelby Center

(NOTE: DO NOT SIGN THIS DOCUMENT UNLESS AN IRB APPROVAL STAMP WITH CURRENT DATES HAS BEEN APPLIED TO THIS DOCUMENT.)

INFORMED CONSENT
for a Research Study Entitled
Sequencing Human Tasks: A New Paradigm for Scheduling Research – Part III

You are invited to participate in a research study that seeks to determine physiological responses to the workloads associated with various tasks performed during order picking. This study is being conducted by Bobbie Watts, PhD Candidate under the direction of Dr. Jerry Davis, Associate Professor in the Industrial and Systems Engineering Department. We hope to learn if sequencing the picks by workload provides any physiological benefit to workers engaged in these activities and use this data to develop physiological constraints for order picking scheduling models if so. You were selected as a possible participant because you are a student in INSY 3021 or INSY 7090 and are between the ages of 19 and 65.

What will be involved if you participate? If you decide to participate, we will ask you to wear a strap around your chest to monitor your heart rate, an armband monitor to measure energy expenditure (both similar to those worn by runners), and electrodes and sensors to measure muscle activity. While wearing these monitors, you will be asked to do a series of manual material handling operations: lift a box from a pallet on the floor, turn and carry it 42” to a table directly behind you, place the box onto a table, then remove the box from the table, carry it back 42” to the pallet, and lower it down. These activities will be continuously repeated for 12 minutes. The weight of the box (5 lbs, 15 lbs, 25 lbs, or 35 lbs) will change every three minutes in a predetermined sequence until each weight has been lifted. After the sequence is completed you will then be asked to answer a couple of short questions. In addition, we will ask you to perform a series of short 7-second muscle contractions (or MVCs) before and after the sequence. As our study will look at the effect of sequencing work, we will be evaluating the weighted

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Participant’s Initials

boxes in three different sequences (5-15-25-35 lbs, 35-5-25-15 lbs, and 35-25-15-5 lbs) and we will be evaluating each sequence on a different day. Therefore, we intend to have you wear the monitors and sensors and simulate picking on three separate days. Each session, which will include putting on equipment, lifting the randomly selected sequence, intervals of rest, answering short questions, and removing equipment, is expected to last forty minutes. This will require a total study time commitment of approximately two hours. You will be expected to refrain from strenuous exercise (running, biking, swimming, weight lifting, or other cardio workouts) for no less than 12 hours prior to all study sessions. For each study session, you will also be expected to wear a T-shirt and shorts (neither tight against the body) to allow access for the application and removal of data collecting equipment, and comfortable shoes.

Are there any risks or discomforts? There is a small risk for injury (whole body and/or localized muscle fatigue from lifting packages, contusion or toe or foot fracture from a dropped package, or sprain or strain to trunk or extremities) and for discomfort (possible irritation to skin from wearing the data collection devices). If this occurs, you will be responsible for any and all medical treatment if it is sought. However, every effort will be made to provide immediate first aid and/or secure medical attention, if needed. A person certified in CPR and AED will be present at all times. Furthermore, you will receive instructions on proper lifting techniques prior to beginning the study and your physiological responses will be monitored.

Are there any benefits to yourself or others? There is no compensation for participating in this study, however there are potential benefits. Benefits for participating in this research include 30 additional lab grade points for those in INSY 3021 or two activity hours credit for those in INSY 7090. In addition, participating students will have an educational benefit by having the opportunity to participate in an activity related to past and future course work and/or research. If you decide not to participate or are not able to pass the health screening required for inclusion in the study, an alternative activity of equal weight will be provided. Furthermore, the overall purpose of this research is to further aid in the reduction of workplace injuries.

If you change your mind about participating, you can withdraw at any time during the study. Your participation is completely voluntary. If you choose to withdraw, your data can be withdrawn as long as it is identifiable. Your decision about whether or not to participate or to stop participating will not jeopardize your future relations with Auburn University or the Department of Industrial and Systems Engineering.

Your privacy will be protected. Any information obtained in connection with this study and that can be identified with you will remain confidential and anonymous. Information collected through your participation may be used to fulfill educational requirements,

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Participant's Initials

published in a professional journal, and/or presented at a professional meeting. If so, no identifiable information will be included. For data analysis purposes, you will be videoed during each session as well. However, as with all other data collected, this too will be confidential and made anonymous if used for publishing purposes.

If you have any questions about this study, we invite you to ask them now. If you have questions later, please feel free to contact Bobbie Watts at (770) 315 - 9129, or at wattsbj@auburn.edu, and she will be happy to answer them for you. You will be provided a copy of this form to keep.

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Participant's signature	Date	Investigator obtaining consent	Date
Print Name		Print Name	

Appendix 4-B

Material Handling Work Physiology Study Pre-Participation Screening
(Adapted from the Health & Fitness Pre-Participation Screening Questionnaire AHA / ACSM, 1998 & Risk Stratification ACSM, 2000)

Date:	____________________	**Ht (in):**	____________________
Age:	____________________	**Wt (lb):**	____________________
Gender:	____________________		

Assess your health needs by marking true statements

History

You have had:

______	Cardiac Catheterization	______	Congenital Heart Disease
______	Coronary Angioplasty (PCTA)	______	Heart Attack
______	Heart Failure	______	Heart Surgery
______	Heart Transplantation	______	Heart Valve Disease
______	Pacemaker / Implantable Cardiac Defibrillator / Rhythm Disturbance		

Signs / Symptoms

You have had:

______ You experience chest discomfort with exertion

______ You experience unreasonable breathlessness

______ You experience dizziness, fainting, blackouts

______ You experience swelling at the ankles

______ You have a known heart murmur

______ You take heart medications (i.e., blood pressure, cholesterol or blood thinning medications)

Other Health Issues

______ You have back pain / injury

______ You have joint pain / injury (knees, elbows)

______ You are pregnant

(cont'd)

Cardiovascular Risk Factors

______	Family history of heart disease: male family member before age 55; female family member before age 65
______	Cigarette Smoker: current or have quit within last 6 months
______	High Blood Pressure: SBP $\geq$ 140 or DBP $\geq$ 90 OR on medication to control
______	High Cholesterol: Total > 200 or HDL < 35 or LDL > 130 OR on medication to control
______	(-) HDL > 60
______	Diabetes (Type I or Type II) OR on medication to control
______	Obesity: BMI > 30 or waist > 39in
______	Sedentary Lifestyle (less than 30 min of physical activity per day)

Do not write in this section

Risk Stratification

______	LOW	(males age < 45; females < 55 with no signs/symptoms and $\leq$ 1 risk factor)
______	MODERATE	(males age $\geq$ 45; females $\geq$ 55 with no signs/symptoms and $\geq$ 2 risk factor)
______	HIGH	($\geq$1 sign/symptom OR known cardiovascular, pulmonary, or metabolic disease)

Code:

Appendix 4-C

ID		***Date***		
SUBJECT INFORMATION				
Watch #:		Age:		
Gender:		Predicted HRmax (220-age):		
Ht(cm):		Standing Resting HR:		
Standing elbow ht (cm):		85% HRR:		*0.85(HRmax-HRrest) + HRrest*
Wt (kg):				
Max MVC(lbs)		75% MVC(lbs)		
LIFTING INFORMATION				
Sequence Code: (INC, MIX, DEC)		Time lifting began for this sequence:		

	Perceived Effort			
RPE	**After 1st Load**	**After 2nd Load**	**After 3rd Load**	**After 4th Load**
Whole Body RPE				
Back RPE				

Auburn University

Auburn University, Alabama 36849-5346

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Participant’s Initials

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______________________________ ______________________________

Participant's signature Date Investigator obtaining consent Date

______________________________ ______________________________

Print Name Print Name

Appendix 5-B

Material Handling Work Physiology Study Pre-Participation Screening
(Adapted from the Health & Fitness Pre-Participation Screening Questionnaire AHA / ACSM, 1998 & Risk Stratification ACSM, 2000)

Date: ____________________ **Ht (in):** ____________________

Age: ____________________ **Wt (lb):** ____________________

Gender: ____________________

Assess your health needs by marking true statements

History

You have had:

_______	Cardiac Catheterization	_______	Congenital Heart Disease
_______	Coronary Angioplasty (PCTA)	_______	Heart Attack
_______	Heart Failure	_______	Heart Surgery
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Other Health Issues

_______	You have back pain / injury
_______	You have joint pain / injury (knees, elbows)
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(cont'd)

Cardiovascular Risk Factors

_______	Family history of heart disease: male family member before age 55; female family member before age 65
_______	Cigarette Smoker: current or have quit within last 6 months
_______	High Blood Pressure: SBP $\geq$ 140 or DBP $\geq$ 90 OR on medication to control
_______	High Cholesterol: Total > 200 or HDL < 35 or LDL > 130 OR on medication to control
_______	(-) HDL > 60
_______	Diabetes (Type I or Type II) OR on medication to control
_______	Obesity: BMI > 30 or waist > 39in
_______	Sedentary Lifestyle (less than 30 min of physical activity per day)

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_______	HIGH	($\geq$1 sign/symptom OR known cardiovascular, pulmonary, or metabolic disease)

Code:

Appendix 5-C

ID		***Date***		
SUBJECT INFORMATION				
Watch #:		Age:		
Gender:		Predicted HRmax (220-age):		
Ht(cm):		Standing Resting HR:		
Standing elbow ht (cm):		85% HRR:		*0.85(HRmax-HRrest) + HRrest*
Wt (kg):				
Max MVC(lbs)		75% MVC(lbs)		
LIFTING INFORMATION				
Sequence Code: (INC, MIX, DEC)		Time lifting began for this sequence:		
	Perceived Effort			
RPE	**After 1st Load**	**After 2nd Load**	**After 3rd Load**	**After 4th Load**
Whole Body RPE				
Back RPE				