2003

Progressive fatigue effects on manual lifting factors

Anthony D'Wayne Banks

Louisiana State University and Agricultural and Mechanical College

Follow this and additional works at: https://digitalcommons.lsu.edu/gradschool_dissertations

Part of the [Engineering Science and Materials Commons](#)

Recommended Citation

Banks, Anthony D'Wayne, "Progressive fatigue effects on manual lifting factors" (2003). *LSU Doctoral Dissertations*. 2421.

https://digitalcommons.lsu.edu/gradschool_dissertations/2421

This Dissertation is brought to you for free and open access by the Graduate School at LSU Digital Commons. It has been accepted for inclusion in LSU Doctoral Dissertations by an authorized graduate school editor of LSU Digital Commons. For more information, please contact gradetd@lsu.edu.

PROGRESSIVE FATIGUE EFFECTS ON MANUAL LIFTING FACTORS

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The Interdepartmental Program in Engineering Science

by
Anthony D'Wayne Banks
B.S. in Electrical Engineering, Southern University, 1996
M.S. in Industrial Engineering, Louisiana State University, 2002
May 2003

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to Dr. Fereydoun Aghazadeh of the Department of Industrial and Manufacturing Systems Engineering, my major advisor, for his constant support and guidance throughout the long course of the entire study. I would also like to thank the committee members, Dr. Dennis Landin, Dr. Lawrence Mann, Jr., Dr. Ralph Pike, and Dr. Ronald Malone for their advice and helpful criticism. I want to thank Dr. Li Li of the Department of Kinesiology and Dr. Richard Baratta of Louisiana State University Health Sciences Center Department of Orthopaedic Surgery for providing me with invaluable technical advice, guidance, experience, and support. Further, my gratitude is given to Dr. Moshe Solomonow of the Louisiana State University Health Sciences Center Department of Orthopaedic Surgery for providing me with the opportunity to gain practical experience and mentoring in this area of study. Additionally, I would like to thank Dr. Thomas Ray and Dr. Julius Langlinais for their unyielding confidence and encouragement. Special thanks are given to my family and friends who gave me their love, support, understanding, compassion, and patience.

TABLE OF CONTENTS

ACKNOWLEDEGMENTS	ii
LIST OF TABLES	vii
LIST OF FIGURES	xi
ABSTRACT	xiii
CHAPTER 1. INTRODUCTION	1
1.1 Background	2
1.2 Rationale.....	3
1.3 Research Objectives.....	5
CHAPTER 2. LITERATURE REVIEW	7
2.1 Introduction to the Research on Low Back Disorders	7
2.2 Methods of Analyzing Low Back Internal Forces	7
2.3 Low Back Structure and Modes of Injury.....	8
2.3.1 Vertebrae	8
2.3.2 Intervertebral Disc	10
2.3.3 Nerve	11
2.3.4 Ligaments	15
2.3.5 Muscle	17
2.4 Fatigue	19
2.4.1 General Physical Fatigue	19
2.4.2 Local Muscular Fatigue	20
2.4.3 Fatigue-related Changes in Lifting	22
2.5 Factors Associated with Increased Risk of Low Back Pain	23
2.5.1 Individual Factors.....	23
2.5.2 Occupational Factors	24
2.5.3 Factors Associated With Lifting	26
CHAPTER 3. METHODS AND PROCEDURE	29
3.1 Participants	29
3.2 Data Acquisition	29
3.2.1 Session Tasks	30
3.2.1.1 Characteristics of the Lifting Task	30
3.2.1.2 Session I – Determining the Mass of the Load	31
3.2.1.3 Session II –Repetitive Lifting Session	32
3.2.1.3.1 Camera System Calibration	34
3.2.1.3.2 Participant Preparation	35
3.2.1.3.3 EMG Amplifier Adjustment and Eva Setup.	38
3.2.1.3.4 Strength Testing and Subjective Fatigue	
Analysis	39

3.2.1.3.5	Repetitive Lifting Task	40
3.2.2	Methods of Data Collection	40
3.2.2.1	Static Composite Strength	41
3.2.2.2	Dynamic Leglift Floor to Knuckle Height Strength	42
3.2.2.3	Subjective Fatigue	44
3.2.2.4	Kinematic Data	46
3.2.2.4.1	Determining Initiation and End of Lift	48
3.2.2.4.2	Calculation of Kinematic Variables	49
3.2.2.4.3	Calculation of Kinetic Variables.....	55
3.2.2.4.4	EMG Data.....	58
3.2.2.4.4.1	Normalized Maximum MAV Over Course of Lift Cycle.....	59
3.2.2.4.4.2	Normalized Median Frequency	60
3.3	Statistical Protocol	61
3.3.1	Independent Variables	62
3.3.2	Dependent Variables	62
3.3.3	Analysis of Variance Techniques: ANOVA and MANOVA	63
3.3.4	Correlation Analysis	65
CHAPTER 4.	RESULTS	69
4.1	Multivariate Analysis Of Variance	70
4.2	Fatigue Analysis Parameters	70
4.2.1	Analysis of Variance (ANOVA) Results	72
4.2.2	Least Squares Means Test Results	78
4.3	Electromyography Amplitude, Kinematic, And Kinetic Parameters	82
4.3.1	Analysis of Variance (ANOVA) Results	92
4.3.2	Least Squares Means Test Results	96
4.4	Correlation Analysis	100
4.4.1	Canonical Correlation Analysis Results of Entire Subject Pool	100
4.4.1.1	VAR (Fatigue Analysis) Variables and the Canonical Variates	102
4.4.1.2	WITH (EMG Amplitude, Kinematic, and Kinetic) Variables and the Canonical Variates	103
4.4.2.	Principal Factors Analysis Results of Entire Subject Pool	109
4.4.3.	Canonical Correlation Analysis Results According to Lifting Posture	111
4.4.3.1	Canonical Correlation Analysis Results of Semi-squat Lifting Posture	113
4.4.3.1.1	VAR (Fatigue Analysis) Variables and the Canonical Variates	113
4.4.3.1.2	WITH (EMG Amplitude, Kinematic, and Kinetic) Variables and the Canonical Variates	114
4.4.3.2	Canonical Correlation Analysis Results of Semi-stoop Lifting Posture	120

4.4.3.2.1	VAR (Fatigue Analysis) Variables and the Canonical Variates	120
4.4.3.2.2	WITH (EMG Amplitude, Kinematic, and Kinetic) variables and the Canonical Variates	121
4.4.3.3	Canonical Correlation Analysis Results of Stoop Lifting Posture	122
4.4.3.3.1	VAR (Fatigue Analysis) Variables and the Canonical Variate	122
4.4.3.3.2	WITH (EMG Amplitude, Kinematic, and Kinetic) Variables and the Canonical Variates.....	127
4.4.4	Principal Factors Analysis Results According to Lifting Posture	133
4.4.4.1	Principal Factors Analysis Results of Semi-squat Lifting Posture	133
4.4.4.2	Principal Factors Analysis Results of Semi-stoop Lifting Posture	136
4.4.4.3	Principal Factors Analysis Results of Stoop Lifting Posture	139
CHAPTER 5.	DISCUSSION	142
5.1	Postures Employed During Freestyle Lifting Trials	142
5.2	Fatigue Assessment	145
5.3	Kinematic And Biomechanical Force Analysis	151
5.4	Fatigue Inter-Parameter Relationships And Relevance To Freestyle Repetitive Lifting	152
5.4.1	Inter-parameter Relationships of Entire Subject Pool	153
5.4.2	Inter-parameter Relationships of Semi-squat Posture	156
5.4.3	Inter-parameter Relationships of Semi-stoop Posture	157
5.4.4	Inter-parameter Relationships of Stoop Posture	158
CHAPTER 6.	SUMMARY AND CONCLUSIONS	160
6.1	The Hypotheses	160
6.2	Summary Of Research And Conclusions	163
6.3	Contributions To The Literature	167
CHAPTER 7.	RECOMMENDATIONS FOR FUTURE RESEARCH	169
REFERENCES		172
APPENDIX		
A	CONSENT FORM	181
B	SUBJECTIVE FATIGUE RATING FORM	184

C	BRIEF FATIGUE INVENTORY QUESTIONNAIRE	186
D	SIGMAPLOT 2001 KINEMATIC ANALYSIS PROGRAM ...	188
E	SIGMAPLOT 2001 EMG ANALYSIS PROGRAM	203
F	SAS ANOVA/MANOVA/POST-HOC PROGRAM	209
G	SAS CANONICAL CORRELATION ANALYSES PROGRAM	213
H	SAS PRINCIPAL FACTORS ANALYSES PROGRAM	216
I	AVERAGE FATIGUE ANALYSIS, KINEMATIC, AND BIOMECHANICAL FORCE DATA ACROSS ALL PARTICIPANTS	219
J	INSTITUTIONAL REVIEW BOARD APPROVAL DOCUMENTATION	227
VITA		230

LIST OF TABLES

3.1	Individual participant data.....	30
3.2	Numerical interpretation of the Brief Fatigue Inventory.....	46
3.3	Numerical Interpretation of Subjective Fatigue Rating Instrument.....	46
3.4	Summary of dependent variables.....	63
3.5	Summary of parameters observed in interpretation of CCA.....	66
3.6	Summary of parameters observed in interpretation of PFA.....	68
4.1	Summary of multiple analysis of variance for all dependent variables.....	70
4.2	Summary of results of analysis of variance with fatigue analysis parameters as dependent variables.....	76
4.3	Summary of results of least squares means tests utilizing the Tukey-Kramer adjustment for multiple comparisons for normalized vastii lateralis median frequency.....	79
4.4	Summary of results of least squares means tests utilizing the Tukey-Kramer adjustment for multiple comparisons for subjective fatigue rating.....	80
4.5	Summary of results of least squares means test for static composite strength.....	80
4.6	Summary of significant results of least squares means tests utilizing the Tukey-Kramer adjustment for multiple comparisons for dynamic leglift floor to knuckle height strength.....	81
4.7	Summary of results of analysis of variance with electromyography amplitude, kinematic, and kinetic parameters as dependent variables.....	96

4.8	Summary of significant results of least squares means tests utilizing the Tukey-Kramer adjustment for normalized EMG mean absolute value of the lumbar erector spinae across postures.....	98
4.9	Summary of significant results of least squares means tests utilizing the Tukey-Kramer adjustment for normalized EMG mean absolute value of the lumbar erector spinae across time.....	98
4.10	Summary of significant results of least squares means tests utilizing the Tukey-Kramer adjustment for peak forward flexion angle at L5/S1 joint.....	99
4.11	Summary of significant results of least squares means tests utilizing the Tukey-Kramer adjustment for forward flexion angle at L5/S1 joint at the initiation of the lift.....	99
4.12	Summary of significant results of least squares means tests utilizing the Tukey-Kramer adjustment for included knee joint angle at the initiation of the lift.....	100
4.13	Summary of canonical correlation test statistics for entire subject pool.....	104
4.14	Summary of standardized variance of the original variables explained by the canonical variates for entire subject pool.....	105
4.15	Summary of canonical loadings between investigated variables and their canonical variates for entire subject pool.....	106
4.16	Summary of canonical cross loadings between fatigue analysis variables and the electromyography amplitude, kinematic, and kinetic variates for entire subject pool.....	107
4.17	Summary of canonical cross loadings between electromyography amplitude, kinematic, and kinetic variables and the fatigue analysis variates for entire subject pool.....	108
4.18	Summary of eigenvalues for principal factors analysis factors detected for entire subject pool.....	111

4.19	Summary of principal factors analysis factorial loadings between original variables and corresponding factors.....	112
4.20	Summary of canonical correlation test statistics for semi-squat.....	115
4.21	Summary of standardized variance of the original variables explained by the canonical variates for semi-squat posture.....	116
4.22	Summary of canonical loadings between investigated variables and their canonical variates for semi-squat posture.....	117
4.23	Summary of canonical cross loadings between fatigue analysis variables and the electromyography amplitude, kinematic, and kinetic variates for semi-squat posture.....	118
4.24	Summary of canonical cross loadings between electromyography amplitude, kinematic, and kinetic variables and the fatigue analysis variates for semi-squat posture.....	119
4.25	Summary of canonical correlation test statistics for semi-stoop.....	122
4.26	Summary of standardized variance of the original variables explained by the canonical variates for semi-stoop posture.....	123
4.27	Summary of canonical loadings between investigated variables and their canonical variates for semi-stoop posture.....	124
4.28	Summary of canonical cross loadings between fatigue analysis variables and the electromyography amplitude, kinematic, and kinetic variates for semi-stoop posture.....	125
4.29	Summary of canonical cross loadings between electromyography amplitude, kinematic, and kinetic variables and the fatigue analysis variates for semi-stoop posture.....	126
4.30	Summary of canonical correlation test statistics for stoop posture.....	128
4.31	Summary of standardized variance of the original variables explained by the canonical variates for stoop posture.....	129
4.32	Summary of canonical loadings between investigated variables and their canonical variates for stoop posture.....	130

4.33	Summary of canonical cross loadings between fatigue analysis variables and the electromyography amplitude, kinematic, and kinetic variates for stoop posture.....	131
4.34	Summary of canonical cross loadings between electromyography amplitude, kinematic, and kinetic variables and the fatigue analysis variates for stoop posture.....	132
4.35	Summary of eigenvalues for principal factors analysis factors detected for semi-squat posture.....	135
4.36	Summary of principal factors analysis factorial loadings between original variables and corresponding factors for semi-squat posture.....	135
4.37	Summary of eigenvalues for principal factors analysis factors detected for semi-stoop posture.....	137
4.38	Summary of principal factors analysis factorial loadings between original variables and corresponding factors for semi-stoop posture.....	138
4.39	Summary of eigenvalues for principal factors analysis factors detected for stoop posture.....	141
4.40	Summary of principal factors analysis factorial loadings between original variables and corresponding factors for stoop posture.....	141
5.1	Summary of lifting postures observed under freestyle lifting condition during experiment.....	144

LIST OF FIGURES

2.1	Lumbar vertebrae and how they appear in the vertebral column.....	9
2.2	The spinal unit.....	9
2.3	Parts and configuration of a typical lumbar vertebra.....	10
2.4	Configuration of the intervertebral disc within a spinal unit.....	12
2.5	Orientation of the sciatic nerve within the lower extremity.....	13
2.6	Spinal nerve configuration within spinal canal in the lumbosacral region.....	14
2.7	Anterior and medial cross-sectional views of ligaments of intact lumbar spine.....	15
2.8	Stress-strain properties of ligament tissue.....	16
3.1	Experimental task setup.....	32
3.2	Experimental Session II equipment configuration layout.....	33
3.3	Configuration of EMG electrode pair placement.....	36
3.4	Configuration of marker placement.....	37
3.5	Eight-segment biomechanical model.....	47
4.1	Normalized Median Frequency of the Thoracic Erector Spinae vs. Time.....	72
4.2	Normalized Median Frequency of the Lumbar Erector Spinae vs. Time.....	73
4.3	Normalized Median Frequency of the Vastii Lateralis vs. Time.....	73
4.4	Subjective Fatigue Rating vs. Time.....	74
4.5	Normalized Static Composite Strength vs. Time.....	74
4.6	Normalized Dynamic Leglift Floor to Knuckle Height Strength vs. Time.....	75

4.7	Normalized Dynamic Leglift Floor to Knuckle Height Strength by Posture vs. Time.....	81
4.8	Normalized Thoracic Erector Spinae Mean Absolute Value vs. Time.....	85
4.9	Normalized Lumbar Erector Spinae Mean Absolute Value vs. Time.....	85
4.10	Normalized Vastii Lateralis Mean Absolute Value vs. Time.....	86
4.11	Duration of Lift Cycle vs. Time.....	86
4.12	Peak Vertical Acceleration of the Load vs. Time.....	87
4.13	Average Force on the Hands During the Lift vs. Time.....	87
4.14	Peak Forward Flexion Angle of L5/S1 Joint vs. Time.....	88
4.15	Peak Angular Extension Velocity of L5/S1 Joint vs. Time.....	88
4.16	Peak Shear Force Acting on L5/S1 Joint vs. Time.....	89
4.17	Peak Compression Force Acting on L5/S1 Joint vs. Time.....	89
4.18	Peak Inertial Moment Acting on L5/S1 Joint vs. Time.....	90
4.19	Integrated Inertial Moment Acting on L5/S1 Joint Over a Single Lift vs. Time.....	90
4.20	Forward Flexion Angle of L5/S1 Joint at Initiation of Lift vs. Time.....	91
4.21	Included Angle of Knee Joint at Initiation of Lift vs. Time.....	91
5.1	Subjective fatigue ratings of individual participants.....	149

ABSTRACT

Much evidence suggests that the cause of lower back pain (LBP) and injury is frequently related to the posture of lifting, the load, muscle fatigue, and other factors. The purpose of this study was to evaluate the effect of progressive fatigue on factors that have previously been associated with increased risk of LBP in various occupational settings, during a repetitive lifting task where freestyle lifting technique was utilized. A laboratory experiment was conducted to evaluate several fatigue analysis, electromyography amplitude, kinematic, and kinetic parameters of repetitive freestyle lifting during a 2-hour lifting period. Each of ten (10) young adult male participants lifted a load from floor height to a lowering platform of 76cm height at a rate of 4 lifts/minute. The mass lifted was determined utilizing the psychophysical approach. The task consisted of 8 consecutive 15-minute periods of lifting, before, between, and after which subjective fatigue rating and strength measurements were taken, and during which kinematic variables were recorded.

Effect of time, at $\alpha=0.05$ level, was observed on subjective fatigue rating ($p<0.0001$) and on static strength ($p=0.0184$). Subjective fatigue rating increased over time, indicating that the participant “felt” increasingly fatigued as the experiment progressed. Static composite strength decreased an average of 20% from the beginning to the end of the experiment. Effect of lifting posture (semi-squat, semi-stoop, and stoop) was observed on peak trunk flexion angle ($p=0.0122$), trunk flexion angle at initiation of the lift ($p=0.009$), and knee angle at initiation of the lift ($p=0.0007$), indicating that in freestyle lifting, participants assume quantitatively different lifting techniques. A significant effect of the time-posture interaction was observed on the dynamic leg lift

floor to knuckle height strength (0.0237), indicating that dynamic strength may change depending upon lifting posture selected. No generalizable effect of the independent variables was observed on the remaining parameters for all participants. Indicators of general physical fatigue, particularly dynamic floor to knuckle height leglift strength and subjective fatigue rating, were observed to possess some significant predictive capability in variation of a number of kinematic and force parameters.

CHAPTER 1

INTRODUCTION

The Kansas Department of Human Resources (2000) cites manual lifting as the highest classified cause (19.6%) of mishap incidence and also as the highest classified cause (31.1%) of injury on the job. The average compensable cost reported for injury resulting from lifting was \$11,793. In the workplace today, it is reported that the second greatest reason for lost workdays is injuries that are due to overexertion when performing lifting tasks (Snook, 1988). It is estimated that 2% of the U.S. workforce suffers compensable back injuries for a total of over 500,000 injuries annually, and that low back cases constitute about 16% of all workers compensation cases and are responsible for 33% of the total cost (Andersson, 1998; Bernard, 1997).

Recent studies indicate that 75 – 85% of all people will experience back pain in some form during their life and that back pain is the most frequent cause of activity limitation in people below the age of 45, the third ranking reason for surgical procedures, and the fifth most frequent reason for hospitalization (Andersson, 1998). With Americans making nearly 20 million physician office visits per year for back complaints, back pain is the second most frequent reason for physician visits, accounting for about 2.8% of all office visits (Hart, et *al.*, 1995; National Academy of Sciences, 2001). Frymoyer (1989) estimates that 9.2 million Americans are presently impaired and 2.4 million are disabled by low back pain. The National Academy of Sciences (2001) estimates that there were 5.6 million work-related back pain cases in 1999 and that approximately 4.6% of the working population lost at least one workday as a result of work-related back pain, with an average of 9.2 lost workdays per work-related case.

Each year, the estimated 600,000 back injuries in the United States cost industry 10 to 14 billion dollars in workers' compensation costs and up to 149 million workdays annually (Occupational Safety and Health Administration, 1992; National Academy of Sciences, 2001). The National Institute for Occupational Safety and Health (1991) reports that the total cost of back injury disabilities, including direct, indirect, and social costs is between 30 billion and 60 billion dollars annually.

1.1 Background

Numerous studies indicate that heavy loading on the human lumbar spine during physical activities can contribute to low back pain and lower back injuries (Schultz and Andersson, 1981), as any time severe stress is placed on the connective tissue of the spine, an injury may occur. Despite technological advancements and automation, manual material handling remains highly present in industry. Currently, it is believed that the primary cause of back injuries is overexertion associated with manual material handling tasks (Kim and Chung, 1995). Daily common lifting tasks have been found to impose a tremendous amount of stress on the lower back in that the stresses imposed are often related as much to the posture of the operator as they are to the weight being lifted (Shultz et. al, 1982). In addition to the pain and suffering of the injured person, and the costs involved, there is the litigation factor that must be considered. An employee who suffers from lower back injury may sue the company on the basis of health hazardous environments, physical damage, and low work potential for the future (Hsu, 1987). These types of lawsuits often result in bad publicity and low worker morale. Therefore, it is necessary to determine safe lifting procedures in the working environment and in job design.

A number of recent studies have indicated that there is a relationship between occupational tasks involving frequent bending, as in repetitive lifting tasks, and increased risk of low back disorders (National Academy of Sciences, 2001). In repetitive lifting tasks, low back injury has often been reported resulting from loads normally well below expected tolerance levels. These occurrences have commonly been attributed to possible changes of physiological mechanisms and load distributions due to fatigue. Recent studies have also indicated that, in repetitive lifting tasks, after a person experiences some level of fatigue, the lifting strategy utilized may change (Potvin, 1992; van Dieen and Toussaint, 1996; van Dieen *et al.*, 1998; Sparto *et al.*, 1997), possibly introducing factors which increase the risk of low back disorder. No studies were found, however which attempt to quantify levels of fatigue on the continuum and determine how the factors associated with the resulting lifting techniques change accordingly. This is knowledge that will be essential in future attempts by researchers and practicing ergonomists to appropriately design work-rest and task rotation cycles as related to repetitive lifting tasks to ensure maximum productivity while limiting the increased risk of lower back disorders related to fatigue. An understanding of how the process of fatigue affects lifting technique and factors related to increased risk of low back disorders in repetitive lifting tasks on a continuous basis is needed.

1.2 Rationale

There has been much effort to reduce the incidence of lower back injury. It is commonly agreed that the cause of lower back pain and injury is frequently related to the posture of lifting, the load, muscle fatigue, and other factors. Many investigations (Bernard, 1997; Norman *et al.*, 1998, National Academy of Sciences, 2001) have

demonstrated that there is a clear relationship between low back disorders and factors of lifting such as frequent bending, peak moment, shear, and compression forces at L5/S1, integrated moment at L5/S1, trunk sagittal angle (flexion), peak trunk velocity, and average force on the hands. One effective way for reducing the incidence of lower back pain and injury is to design the occupational task to minimize the back injury potential, as the National Academy of Sciences (2001) has reported that "studies reviewed show that a change in the risk of low back disorders was established when changes were made to the physical aspects of work."

Several studies (Potvin, 1992; van Dieen and Toussaint, 1996; van Dieen et al., 1998; Sparto et al., 1997) have demonstrated that as a person performs a manual lifting task expected to impose or which ultimately results in muscular fatigue, or if isolated muscle fatigue is induced otherwise (Trafimow et al., 1993), the individual's coordination and lifting strategy may tend to change, thereby changing the stresses imposed on the lower back. Most previous studies have either made the assumption that the tasks analyzed were rigorous enough to fatigue the subject and not attempted to quantify measures of fatigue or have used a measure of complete exhaustion (subject no longer able to continue) as their only fatigue measure, thereby defining fatigue as a one-time discreet occurrence. The one study (Potvin, 1992), which analyzed indices of fatigue at intermittent points throughout the experiments, used only static strength tests and measures of local muscle fatigue and did not analyze the kinematic parameters of the lifting task as local muscle fatigue progressed or consider functional or subjective measures of fatigue.

Unlike previous studies, the current study assesses the effects of fatigue on manual lifting factors in a repetitive lifting task by analyzing kinematic and kinetic properties of the lifting task while concurrently analyzing several indices of both general physical and local muscular fatigue. Fatigue indices as well as kinematic and kinetic variables are observed and assessed in intermittent intervals throughout the performance of the experimental task such that any apparent change can be observed on its continuum and any changes may be viewed as progressions rather than as single event occurrences. This approach allows the current study to assess lifting factors associated with increased risk of LBD directly in relation to fatigue, rather than simply in relation to time, as has generally been done in preceding research. Further, concurrent intermittent observation and assessment of the various fatigue indices provide greater insight into how these indices behave with respect to one another.

In order to enable future design of manual lifting tasks such that there is appropriate ergonomic intervention and a reduced risk of lower back disorders, it is important to gain an understanding of how lifting kinematic and kinetic parameters change with the progression of fatigue. The results of this study can be used to obtain a better understanding of the nature of fatigue in repetitive manual lifting tasks and its effect on factors associated with increased risk of low back disorders to aid in more informed job design and intervention.

1.3 Research Objectives

The primary objective of this study was to determine the effects of progressive fatigue during a manual lifting task, where freestyle lifting technique was utilized, on several parameters associated with lifting strategy that have been found to be highly

correlated with reported low back pain in various occupational settings. The parameters observed in this study included posture at the initiation of the lift (trunk inclination and knee angles), peak vertical load acceleration, average force on the hands, peak lumbar vertebral (trunk) flexion, peak lumbar vertebral (trunk) extension velocity, peak shear force at L5/S1, peak compression force at L5/S1, peak moment at L5/S1, and integrated moment at L5/S1. In addition, the study has also served to compare between the static, dynamic, and subjective parameters used to quantify levels of dynamically induced fatigue in a manual lifting task. Specifically, the objectives of this study were as follows.

- To utilize force production capacity, myoelectric muscle activity properties, and subjective measures of fatigue to indicate and verify any general physical and/or any local muscular fatigue as a progression in relation to a bout of repetitive manual freestyle lifting.
- To determine any changes in kinematic and/or kinetic factors associated with manual lifting technique or strategy observed over a prolonged bout of repetitive manual freestyle lifting.
- To clarify the relationship between any observed changes in assessed indicators of fatigue associated with repetitive manual freestyle lifting and any observed changes in associated kinematic and kinetic factors.
- To determine any relationship between the indices used to indicate various measures of general physical and local muscular fatigue during a prolonged bout of repetitive manual freestyle lifting.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to the Research on Low Back Disorders

Low back pain is a serious problem and among published studies, the lower back is one of the most common areas analyzed by researchers (Hsu, 1987). Although only 10 to 20% of patients receive a definitive clinical diagnosis to explain their back pain, it is generally agreed upon that overexertion, repetitive bending and twisting motions of the trunk during the tasks are the main cause of low back disorders (Kim and Chung, 1995). Postures, both for dynamic lifting and static work have been extensively studied as they relate to the stresses imposed on the low back.

2.2 Methods of Analyzing Low Back Internal Forces

In early studies (Nachemson and Morris, 1964; Andersson et al., 1974; Andersson et al., 1977; and Ortengren et al., 1981), postural stresses imposed on the lower back were evaluated by researchers using lumbar intradiscal pressure measurements as an indicator, as well as measurements of intra-gastric pressure. Due to the invasive and restrictive nature of these measurement procedures, their use was generally impractical and measurements could only be taken in a limited number of clinical situations. Later, the common indication of load on the lower back became the measurement of myoelectric activity of the trunk musculature (Andersson et al., 1979; Shultz et al., 1981; and Marras et al., 1996). Along with the measurement of myoelectric activity, techniques of optimization (Cholewicki et al., 1995) have been frequently utilized in attempts to improve anatomical detail. The resulting optimization models have oftentimes been prohibitively cumbersome and collectively suffer from mathematical indeterminacy (McGill and Norman, 1993), where the number of unknown forces in muscles and other

tissues is greater than the number of equations available to determine them. Beyond the analysis of myoelectric activity, biomechanical modeling (Shultz et *al.*, 1981; Shultz et *al.*, 1982; and Granada et *al.*, 1993) has become prominent in the evaluation of postures and the stresses imposed due to them as a result of the ease in calculation, accurate validation in agreement with intradiscal pressure and myoelectric activity and their limitless applications.

2.3 Low Back Structure and Modes of Injury

Injury, or failure of a tissue, occurs when the applied load exceeds the failure tolerance or strength of the tissue. In order to appreciate the possible mechanisms of low back disorders, it is necessary to gain a general understanding of the structures which comprise the lower back and the effects of the properties of magnitude, repetition, and duration of the forces acting on the various components. The lumbosacral spine region consists of the five lumbar vertebrae (Figure 2.1) and sacrum connected by an intervertebral disc and ligaments, as well as associated nerves and musculature. The smallest structure of the spine containing all of the spinal components is the functional spinal unit (Figure 2.2), consisting of two vertebrae, joints, discs, muscles and ligaments, neural and vascular elements.

2.3.1 Vertebrae

The configuration of the lumbar vertebra is depicted in Figure 2.3. Each of the five lumbar vertebrae consists of a drum-shaped body (VB), pedicle (P), transverse process (TP), lamina (L), spinous process (SP), and vertebral foramen (VF). The lumbar vertebrae contain larger, and therefore stronger, bodies than the vertebrae above them (Gray, 1977).

Figure 2.1 Lumbar vertebrae and how they appear in the vertebral column (from Bodguk, 1999)

Figure 2.2 The spinal unit consists of two vertebrae, joints, discs, muscles and ligaments, neural and vascular elements (from Porterfield and DeRosa, 1998)

The strength of the vertebral body is derived from the trabecular bone core and is primarily a function of the vertebral body area and the bone density. It has been demonstrated in numerous studies (Hansson *et al.*, 1980; Brinckmann *et al.*, 1989) that a spine in neutral position under compressive load may result in bony failure. Brinckmann *et al.* (1989) report that the compressive strength of lumbar vertebrae ranges between 2 and 12 kiloNewtons (kN), with large inter-individual variation, and they have been able to estimate vertebral body compressive strength in-vivo to within 1 kN. Brinckmann *et al.* (1988) have also demonstrated that repetitive compression loads greatly increase the probability of vertebral failure. It was observed that in 5000 cycles of compression load, the probability of vertebral failure increase ranges from 36% at a 30-40% compressive load level to 92% at a 60-70% load level. It was further observed that in 10 cycles of compressive load at a 60-70% load level, an 8% probability of failure was realized.

Figure 2.3 Parts and configuration of a typical lumbar vertebra: top (left) and side (right) views (adapted from Bogduk, 1999)

2.3.2 Intervertebral Disc

The intervertebral disc acts as a flexible spacer or cushion between adjacent vertebrae and permits rotation and translation between them. Its configuration is depicted

in Figure 2.4. Each disk is comprised of a band of fibrous fibrocartilage, the annulus fibrosus, encompassing a gelatinous core, the nucleus pulposus. In the lumbar spine, the thickness of the discs is greatest in the front and is responsible for the anterior convexity of that portion of the spine. Hutton and Adams (1982) demonstrated that the intervertebral disc in a neutral position is very strong under compression force, as cadaver discs in their study were, on average, able to withstand single compression loads of more than 10 kN before failure occurred. In most cases, the resultant failure was in the vertebral endplate, which forms the boundary between the disc and the vertebral body. Where vertebral segments were wedged to simulate hyperflexion (extreme bending of the spine), Adams and Hutton (1982) observed a prolapse of over 40 percent of the discs tested at an average of 5.4 kN, indicating the decreased compressive strength of the intervertebral disc in the hyperflexed spine. Adams and Hutton (1985) observed in a later study, where repeated loading of the disc was applied, that discs in a neutral position failed at an average of as low as 3.8 kN. These findings are consistent with the observation that disc herniation is the result of cyclic loading or prolonged and sustained loading in deviated spine postures (McGill, 1997).

2.3.3 Nerve

Pain and dysfunction to the nerve root canal are usually secondary to some other disease or injury to the spine, such as intervertebral disc disease or segmental instability resulting in perturbation to the nerve root complex. Nerve root pain, however, is not necessarily observed where compression or tension of the nerve root alone is present. Concurrent inflammation of the nerve root is also necessary for symptoms and to present. Symptoms consistent with nerve root irritation include pain below the knee; leg pain

Figure 2.4 Configuration of the intervertebral disc within a spinal unit (from Porterfield and DeRosa, 1998)

produced by straight-leg raise; excessive pain irradiation with gentle spinal motions; leg pain greater than accompanying back pain; and leg pain present in clearly demarcated region. Symptoms consistent with nerve root compression include change in reflex; muscle weakness; muscle atrophy; and sensory loss over defined dermatome. Some nerve dysfunctions that can arise from such nerve root irritation or compression and concurrent inflammation are sciatica, spinal stenosis, and cauda equina syndrome.

Sciatica has been defined as a prevalent and painful condition resulting from compression or tension on the sciatic nerve (Potvin, 1992). The sciatic nerve (Figure 2.5), which is the longest nerve in the body, originates from the distal spinal cord and extends along nearly the entire length of the hind leg, giving rise to branches as it progresses distally. Some general symptoms of sciatica can be numbness or hypersensitivity, tingling, pain, or weakness in the lower back and radiating below the knee. Sciatica is most commonly a result of prolapsed intervertebral discs, where the

Figure 2.5 Orientation of the sciatic nerve within the lower extremity (from Jabre and Hackett, 1983)

annulus fibrosis is torn and the nucleus pulposus has herniated outside of the disc, and rests on the root of the sciatic nerve, applying compressive pressure. Inflamed or spastic muscles of the lower back or buttocks have also been reported to irritate or compress the sciatic nerve. In clinical diagnosis tests, the probability of disc prolapse as the cause of sciatica decreases as the degree of hip flexion required to initiate pain increases (Frymoyer, 1989; Potvin, 1992).

Progressive spinal degeneration can produce bone spurs in the spinal canal, possibly as a result of excess motion at the spinal segment. Constriction or reduction of the spinal canal may cause the bone spurs to press on the nerve root, resulting in spinal

stenosis. Spinal stenosis presents as pain and nerve dysfunction in the legs. Further complication may arise as a result of the narrow spinal canal as compression may not allow sufficient circulation of blood to the nerves within the spinal cord. This can become particularly problematic when an individual is active as greater blood supply is necessary during activity as opposed to a resting state.

In the most severe cases, some neurogenic type maladies can be potentially life-threatening. Figure 2.6 depicts the configuration of the spinal nerves within the lumbosacral region of the spinal canal. Few cases of intervertebral disc herniation result in expansion by such proportion that the herniation fills the entire spinal canal. The extreme pressure on the spinal nerves may cause paralysis of the muscles that control the bowels and bladder, potentially exposing the body to hypertoxicity.

Figure 2.6 Spinal nerve configuration within spinal canal in the lumbosacral region (from Bogduk, 1999)

2.3.4 Ligaments

The vertebral bodies are united by ligaments, which hold the bone together while allowing some measure of movement. The ligaments are elastic structures with an elastic limit. Figure 2.7 depicts the configuration of the ligaments of the intact lumbar spine, to include the anterior longitudinal (ALL), posterior longitudinal (PLL), intertransverse (ITL), supraspinous (SSL), and interspinous (ISL) ligaments and the ligamentum flavum.

Figure 2.7 Anterior (left) and medial cross-sectional (right) views of ligaments of intact lumbar spine (from Bogduk, 1999)

Numerous studies have confirmed that ligament tolerances are affected by the load rate (Norman et *al.*, 1998; National Academy of Sciences, 2001) and that risk of ligament failure increases with increased bending motions, specifically velocity. Further, it may be noted that interspinous ligaments create anterior shear forces on the flexed spine in a forward bending position. Damage to ligament tissue resulting in micro- or macro-failure occurs when the level of stress applied to the ligament exceeds the elastic limit of the tissue. Adams and Dolan (1995) report that in in vitro studies, damage to

ligament tissue was observed to occur at about 60 Newton-meters (Nm). It has been observed that, within the elastic limit of the ligament tissue, where a constant load is applied for a sustained period of time, the length of the tissue increases (Solomonow *et al.*, 1998; Bodguk, 1997), such that “creep” is induced. Once the ligament tissue is unloaded, the tissue undergoes hysteresis, regaining shape/length characteristics at a different, slower rate than that at which the elongation occurred. Several properties of the ligament tissue under stress are depicted in Figure 2.8.

Figure 2.8 Stress-strain properties of ligament tissue. (a) Stress-strain curve for a ligament; (b) Creep under constant load over time; (c) Hysteresis; (d) Fatigue failure (adapted from Bogduk, 1999)

Ligaments appear to require long periods of time to regain structural integrity once injured (National Academy of Sciences, 2001). Results of feline studies (Stubbs et al., 1998; Solomonow et al., 1998; Solomonow et al., 2003) have demonstrated the recruitment of paraspinal muscle where loads were applied to ligaments of the lumbar spine that were beyond their elastic limit. Further studies (Solomonow et al., 1999; Gedalia et al., 1999) demonstrated that the same paraspinal muscles, after cyclic loading, lose a great deal of reflexive activity as a result of desensitized mechanoreceptors and that the necessary recovery time of these muscles is extensive. Repetition of cyclic loading at levels below the ultimate tensile stress limit of the tissue has also been reported to cause the tissue to become less stiff and fail at substantially less stress than the initial ultimate tensile stress. This occurrence is known as fatigue failure. These properties may further expose the ligaments to damage under cyclic loading.

2.3.5 Muscle

There are several proposed muscular mechanisms, aside from uncommon muscular diseases, frequently thought to be responsible for incidences of low back pain. The cardinal conditions purportedly responsible for pain in the low back musculature are sprain, spasm, imbalance, and trigger point (Bogduk, 1999). It is reported that acute or chronic lumbosacral sprain or “strain”, implying symptoms originating in the lumbar musculature, is the most common diagnosis reported for low back disorders (Potvin, 1992), though there is no solid, verified definition available of muscle “sprain,” which lends itself to any quantifiable characteristics. Reasoning for the implication of lumbar muscular sprain as a cause of low back pain stems from the results of animal studies that demonstrated that when muscles are forcibly stretched against contraction, they generally

fail at the myotendinous joint (Bogduk, 1999). It has been presumed that the inflammatory repair response caused by the resulting lesion would be a reasonable source of pain. In the case of back muscles, where such lesions might be incurred, most presumed sites of injury are deep and therefore not accessible to clinical examination. For this reason, there is a lack of direct evidence of any such lesion to verify the actual occurrence or existence of sprain in the lumbar musculature.

The musculature of the lumbar spine acts to aid in the stabilization and movements of the spine as well as to perform protective functions of the spinal tissues (Richardson et al., 1999). It is often believed that as a result of some postural abnormality, or secondary to some related source of pain, muscles may be chronically active, resulting in pain from spasm. Evidence of spasm as a cause of low back pain has been inconclusive and there is no clear explanation of precisely how pain from the spasms arises. In the low back, muscle imbalance is thought to be a source of pain in the musculature. This is thought to be an imbalance in tone between the flexors and extensors related to the lumbopelvic region or between the postural musculature, including the abdominal muscles. Generally, it is unclear how the imbalance comes to be painful, and specifically from which muscles or related joints the pain arises.

Acute or chronic repetitive strain of the musculature of the low back has been implicated in the development of painful “trigger points.” These trigger points symptomized as extreme tenderness located within externally accessible bands of taut muscle fibers and are capable of producing local and referred pain and a characteristic elicited twitch response. Trigger points are thought to represent areas of “hypercontracted muscle cells that deplete local energy stores and impair the function of

calcium pumps, thereby perpetuating the contraction” (Bogduk, 1999). Multifidus, longissimus, and iliocostalis muscles have been reported to be affected by trigger points.

2.4 Fatigue

Fatigue may be defined as a gradual or progressive loss of force-generating capacity resulting from physical activity (Potvin and Norman, 1993; Fulco et *al.*, 1995), or an impairment of performance that initially includes a sense of need to increase effort to maintain a desired muscle power output level, and eventually a failure to generate that output even with higher effort (Kincaid, 1997). Many studies (Fraser et *al.*, 2000; van Dieen et *al.*, 1996, 1998; Trafimow et *al.*, 1992) have indicated that there may be a change in manual lifting strategy where some level of fatigue has been experienced. Fatigue can be manifested in one or a combination of two ways, general physical fatigue and local muscular fatigue.

2.4.1 General Physical Fatigue

General physical fatigue of a physiological nature is thought to be a warning mechanism preventing overstraining the organism (Astrand and Rodhal, 1977). Subjective symptoms of general physical fatigue may range from a slight feeling of tiredness to complete exhaustion. During prolonged, submaximal work, this “sensation” of fatigue generally coincides with significant reduction or depletion of glycogen deposits in the liver and working muscle, a drop in blood glucose, and increase in blood lactate (Kroemer et *al.*, 1986; McArdle et *al.*, 1996), such that no steady-state can be achieved. It has been reported (Astrand and Rodhal, 1977; Petrofsky and Lind, 1978) that subjective feelings of fatigue usually occur at the end of an 8-hour work day, where the average work load exceeds 30 to 40 percent of the individual’s maximal aerobic capacity,

and certainly when the work load exceeds 50 percent of the maximal aerobic capacity. With sufficient rest, general physical fatigue is completely recoverable.

2.4.2 Local Muscular Fatigue

Local muscle fatigue occurs under prolonged and strong muscle contractions, when there is an inability of the contractile and metabolic processes to continue the supply of needed energy carriers and remove the metabolic by-product, lactic acid (Kroemer *et al.*, 1986), yielding and increased lactic acid content in the active muscle. Under a single sustained contraction, this process is precipitated by the interruption of blood flow through the muscle, which leads to complete muscle fatigue. The mechanisms of muscular fatigue are not clearly understood, but it is believed that there are contributions from central nervous system pathways, anterior horn cell performance, and the muscle at several sites (Kincaid, 1997).

Verification of the existence of local muscular fatigue has been quantified in a number of ways. As fatigue is partially defined as the “loss of force generating capacity,” local muscular fatigue has often been identified (Fulco, *et al.*, 1995; Potvin and Norman, 1993; Potvin, 1992) by a decrease in the force generated by a specific muscle or muscle group during maximal voluntary contraction (MVC), or by a decrease in the time that a subject is able to maintain some controlled, submaximal level of MVC. An increase in the amplitude of myoelectric (EMG) activity of the active muscles during MVC or some submaximal, controlled level of MVC has also been used as a frequent measure of fatigue. Limitations of the previous methods as sole indicators of local muscular fatigue have been noted (Roy, *et. al.*, 1988; Potvin and Norman, 1993), as all of these factors are highly dependent upon motivation of the subject, while EMG amplitudes are also sensitive to both muscle force and fatigue levels. In conjunction with the

previous measures of fatigue assessment, analysis of the frequency spectrum of the active muscles' EMG activity has often been used (Petrofsky and Lind, 1978; Roy, et. *al.*, 1988; Dolan et *al.*, 1994; Merletti et *al.*, 1990; Yoshikawa et *al.*, 1994) to identify the occurrence of some level of local muscular fatigue. Frequency parameters frequently analyzed have included mean power frequency and median power frequency (De Luca, 1997), which have been shown to decrease with fatigue, and the power component in the low-frequency (5-30Hz) component of the signal (Dolan, et *al.*, 1994), which increases with the progression of fatigue. Roy et *al.* (1988) points out that EMG spectral measurements are more independent of subject motivation and require less demanding contractions than other methods of fatigue assessment.

Measurements of fatigue, related to dynamic lifting, have almost exclusively been done using static measures. That is, the parameters previously discussed have typically been recorded and analyzed under the sustainment of MVC or some submaximal, controlled level of MVC, rather than during dynamic exertion. Few studies (Petrofsky and Lind, 1978; Kim et *al.*, 1992; Sang and Kim, 1995; Fraser et *al.*, 2000) have measured myoelectric activity during dynamic lifting tasks and, further, analyzed the EMG parameters to attempt to verify some measure of fatigue. Fraser et *al.* (2000) did not analyze the frequency domain of the EMG signal and they found no significant change in peak EMG amplitude of the trunk muscles examined between rest and the condition considered to be fatigue. In the remaining studies, the activity of the frequency parameters observed (shift of power to lower frequencies) were consistent with those typically used to identify local muscular fatigue under sustained isometric contraction.

2.4.3 Fatigue-related Changes in Lifting

Numerous researchers have examined changes that may occur in lifting parameters after some level of fatigue is experienced, with mixed results. Kim *et al.* (1992) observed, in freestyle repetitive lifting, increases in mean load acceleration and peak lumbosacral compressive force, with repeated bouts where fatigue was indicated. Potvin (1992) reported no “generalizable and consistent effect of fatigue” and “no variables which showed the same trend for all subjects” in his investigation of lifting parameters in association with fatigue in repetitive lifting utilizing the freestyle technique, though an increase in peak flexion angle was observed in high frequency (8/minute) lifting after 20 minutes. van Dieen and colleagues (1996) examined the effect of long bouts of repetitive lifting and lowering, assumed to induce fatigue, on kinematic parameters in squat and stoop lifting. A decrease in the phase lag between knee and hip extension was observed during squat lifting, but no other changes in lifting strategy were observed, nor was a change in lumbosacral torque found. In a similar study, analyzing repetitive squat lifting, Lee *et al.* (1989) observed increases in lifting acceleration and lifting speed after two hours, yet no decrease in static lifting strength was observed. In a later study by van Dieen *et al.* (1998), which examined kinematics in repetitive lifting alone, utilizing the freestyle technique, several changes in kinematic lifting parameters were observed. Trunk extension velocity was observed to decrease while hip extension velocity decreased, thereby increasing the phase lag between hip and trunk extension. Over time, it was reported, subjects changed to a lifting posture, which resembled the stoop technique, with decreased flexion at the knee and increased trunk flexion. Also, as lifting continued, an increase in twisting of the trunk was observed.

Trafimow *et al.* (1992) investigated kinematics of freestyle lifting before and after fatiguing the quadriceps muscle. Several kinematic variables were observed to change after fatigue of the quadriceps, to include an increase in trunk extension angular velocity at the time of peak lumbosacral moment and decreases in the knee moment integral and the hip angles before, during, and at the time of peak lumbosacral moment, in essence changing the lifting technique from “more of a squat lift to more of a stoop.” Similar results were obtained by Buhr *et al.* (1999), where rectus femorii and gastrocnemii muscles were weakened using EMG biofeedback and freestyle lifting was observed to change to more of a “backlift.”

2.5 Factors Associated with Increased Risk of Low Back Pain

Low back pain (LBP) has been defined as chronic or acute pain of the lumbosacral, buttock, or upper leg region (Bernard, 1997). While imaging techniques have reportedly been able to demonstrate clearly a structural cause of chronic back pain in only 19% of cases (Liebenson, 1992), the literature indicates that there are many factors that have been associated with an increased risk of developing LBP. The various factors are categorized here as individual factors, occupational factors, and factors associated with lifting.

2.5.1 Individual Factors

A number of studies have been conducted pertaining to the contribution of individual factors to an individual’s increased risk of LBP (Liebenson, 1992 provides an excellent detailed review). An epidemiologic study (Shekelle, 1995), reviewing insurance claims records related to back pain care identified several individual factors found to be related to increased incidence of treatment for back pain, including increasing age, site or location, education level (higher incidence was observed where the education

level was below post-secondary), race, and employment status. Factors not found to be associated in this study were cigarette smoking, obesity, physical activity, general health status, and psychological factors such as stress, depression, and anxiety. Conversely, Liebenson (1992) sites numerous individual studies, which have demonstrated high correlations between each of the previously mentioned factors and incidences of reported LBP or back pain treatment. In addition, Liebenson reports an inverse relationship between both, levels of spinal flexibility and lifting and trunk strength, and incidence of LBP, as well as an increase in reports of LBP with pregnancy. Dolan and Adams (1993, 2000) report larger bending moments, approaching levels predicted to cause structural damage to the low back, in the observed performance of everyday activities, such as putting on socks or sitting on the floor, in subjects with decreased spinal flexibility. Research of Andersson (1998) implicates such anthropometric factors as tallness in association with increased risk of sciatica and disc herniation, and obesity in the increased risk of back pain in general. Chaffin and associates cite increased age (Chaffin and Page, 1994) and, further, the decreased activity, which often accompanies an increase in age (Chaffin and Ashton-Miller, 1991), as a prominent factor in incidence of LBP.

2.5.2 Occupational Factors

A number of occupational factors have been proposed to contribute to the incidence of LBP. Chaffin and Ashton-Miller (1991) report that heavy lifting (which is discussed in detail in section 2.5.3) is associated with an 8-fold increase in the frequency rate of medically treated LBP. In a study of automobile assembly workers, Punnett *et al.* (1991) observed an increase in risk of LBP with increased trunk flexion, with trunk twisting and lateral bending, and with exposure to multiple nonneutral postures and increased exposure time. It has been reported (National Academy of Sciences, 2001) that

as nonneutral posture becomes more extreme, or trunk motions become more rapid, reporting of back disorder is greater.

Marras et al. (1993, 1995), in the evaluation of industrial jobs, found exposure to lumbar load moment to be the single most powerful predictor of low back disorder reporting. In a recent study (Norman et al., 1998) of automotive industry workers, several biomechanical factors were identified and implemented in a predictive model of reporting of LBP. The factors identified were peak lumbosacral shear, integrated lumbar moment over the duration of the shift, peak torso flexion velocity, and usual hand force over the course of the shift. It was noted that, although peak spinal compression and moment were not seen in the best statistical model, they should also be included in occupational evaluation. In the same study, psychosocial factors found to be highly associated with the reporting of LBP were worker perceptions of high physical demand; poor workplace social environment; low job control, but high worker support; high job satisfaction; and better education relative to those who performed similar jobs. Liebson (1992) also cites numerous studies that identify psychological and psychosocial factors, such as distress and job satisfaction indices, and the perception of the job to be emotionally stressful, anxiety-provoking or demanding, as being highly related to reported LBP.

Other occupational factors which have been reported (Chaffin and Ashton-Miller, 1991) to be associated with increased reporting of LPB include postures which require prolonged static exertions, seats that are not ergonomically designed to support the lumbar region, and exposure to low-frequency vibration. It has also been reported (Andersson, 1981; McGill, 1997) that sedentary jobs and prolonged sitting postures have

been associated with an increased risk of disc herniation and LBP. National Academy of Sciences (2001) has concluded that occupational risk of LBP can be identified when ergonomic evaluations properly consider: (1) worker capacity in relation to the job, (2) the load location and weight magnitude relative to the worker, (3) temporal aspects of the work, (4) three-dimensional movements while the worker is lifting, and (5) exposure to multiple risk factors simultaneously.

2.5.3 Factors Associated With Lifting

It has commonly been agreed (Chaffin and Park, 1973; Dolan *et. al*, 1993) that lifting is associated with an increased risk of the development of LBP. Liebenson (1992) reports that lifting and bending account for 33% of all work-related episodes of low back pain. It is not however, sufficient to say that any lifting equates to an increased risk of low back pain. It is therefore necessary to identify and understand the factors associated with lifting, which increase the risk of LBP.

Shultz *et. al* (1982) found that large spinal loads and low back muscle contractions were seen in activities where there was a great amount of trunk flexion. There were found to be smaller loads on the lumbar spine in weight bearing activities under which the trunk angle was 0° than in no weight bearing postures under which the trunk angle was 30° and the subjects' hands were held close to his chest. Marras and Granata (1997) concluded that "combination of lateral shear and compression is the biomechanic mechanism responsible for the increased risk associated with lateral trunk movements." Dolan *et. al* (1993) found that extensor moment and bending torque on a subject's lower back increased greatly as the distance between the lifted load and the subject's body was increased. The 1982 study of Shultz *et. al* suggests that there may be a greater load imposed on the lower back from bending over to pick up a piece of paper

located at a distance away from the body than by lifting a heavy load maintaining its position close to the lifter's body.

It has often been suggested in the literature (Liebenson, 1992; Aghazadeh and Ayoub, 1985; Mital et al., 1986; Waikar et al., 1991) that strength requirements of lifting tasks as compared to the ability of the lifter is related to an increased risk of LBP. Chaffin and Park (1973) found a positive correlation between the incidence of low back pain and increased lifting strength requirements, as assessed by the load location and magnitude of the load lifted. Fathallah et al. (1998, 2000), in evaluation of manual materials handling jobs, have recently demonstrated that elevated levels of combined lateral and twisting velocity patterns were unique to groups with increased low back disorder risk. In the study, load moment and frequency were also found to be correlated with increased risk of low back disorder. Many researchers (McGill, 1997; National Academy of Sciences, 2001; Marras et al., 1993, 1995) have identified occupational lifting frequency or repetition, beyond some protective threshold level, as a factor in risk of LBP, such that exposure to moderate levels of load and frequency of lifting appear to represent the lowest level of risk, while exposure at greater levels represents the greatest level of risk.

Lifting velocity and acceleration have often been implicated as factors in increased risk of LBP. Fathallah et al. (2000) found that in observed jobs where the workers were at high risk of LBP, a “significantly higher 3-D velocity magnitude” was required than in the low risk group, with 22% of the total motion occurring at velocities higher than 20 degrees/second, and it was noted that the lumbar “loading rate vector increased as the speed of the lift increased.” Chaffin and Ashton-Miller (1991) report

that, when lifting is rapidly performed, loads on the spine increase in proportion to the accelerations involved, and that doubling the speed of lifting has been shown to “increase low back loads by at least 50%.”

Other factors that have been observed to relate lifting to an increased risk of LBP are time of day and previous activities. It has been reported (McGill and Norman, 1993; Dolan and Adams, 2000) that, when lifting is performed shortly after rising from bed, the lumbar spine is more resistant to bending due to increased disc fluid content, thereby greatly increasing the bending stresses on the discs and ligaments to or above observed fatigue limits. Activity performed prior to lifting has also been associated with increased risk of LBP. Animal studies (Yoshikawa et *al.*, 1994) have demonstrated that bone strain may increase as muscles become fatigued and that shear strain may increase at a greater rate following the attainment of some level of fatigue. It has also been suggested (McGill and Norman, 1993; McGill, 1997) that lifting after prolonged flexion of the spine may lead to increased risk of LBP or injury, as prolonged full flexion may cause the posterior ligaments to creep. This has been supported by the findings of feline studies (Solomonow et *al.*, 1999), where induced (by cyclic loading) laxity of lumbar ligaments was accompanied by a reduction or elimination in protective reflexive forces applied by the paraspinal muscles.

CHAPTER 3

METHODS AND PROCEDURE

The objective of this research was to determine the effects of progressive fatigue during a manual lifting task, where freestyle lifting technique was utilized, on several parameters associated with lifting strategy that have been found to be highly correlated with reported low back pain in various occupational settings. To achieve this objective, ten (10) male participants were recruited to perform a freestyle manual lifting task for a period of two hours. At fifteen-minute intervals, during the two-hour session, kinematic, strength, and subjective fatigue measurements were recorded and analyzed.

3.1 Participants

Ten (10) young adult males with no apparent physical ailments were recruited as participants. Anyone with a history of serious low-back injury or recent pain or any apparent physical ailments was excluded. All participants were moderately active with some form of regular exercise, though none were involved in competitive sports or daily manual materials handling at the time of the study or in recent years prior to the investigation. Each participant was informed of the demands of the testing procedure and signed an informed consent form, approved by the Louisiana State University Institutional Review Board (IRB), which can be viewed in Appendix A. Participant statistics are presented in Table 3.1.

3.2 Data Acquisition

The design of the experimental task was to fatigue the subjects with a bout of long-term repetitive lifting. The experiment consisted of two lifting sessions. The first session served to familiarize the participants with the lifting task as well as to

psychophysically determine the load to be lifted during the subsequent session. The second session served to provide data to establish that the lifting task provided progressive fatigue and to quantify parameters of interest during the performance of the lifting task.

Table 3.1 Individual participant data

Participant	Age (years)	Height (cm)	Body Mass (kg)	Mass Lifted (kg)
1	23	183.6	84.5	19.5
2	23	177.6	82.8	20
3	22	173.5	83.4	27.5
4	28	177.6	103.2	13
5	28	176.8	92.3	26.3
6	33	180.4	91	11.6
7	23	183.4	74.1	12.5
8	33	173.6	59.1	8
9	23	175.5	64.6	13.1
10	23	163.9	65	8
Mean	25.9	176.59	80	15.95
Std Dev	4.30	5.70	14.08	7.02

3.2.1 Session Tasks

The protocol for each session is presented in this section. The details of the specific data collected is presented in section 3.2.2.

3.2.1.1 Characteristics of the Lifting Task

During each lifting session, each participant performed the lifting task four times per minute (one lift/15 seconds). A digital voice recording was used to instruct the subject to lift at the end of every 15-second interval. The participant was instructed to

stand at a comfortable distance ($>15\text{cm}$ from x-center of load) directly in front of the load with his feet placed symmetrically and comfortably apart. Each participant was then instructed to lift a wooden box of dimensions $46\text{cm} \times 30\text{cm} \times 16\text{cm}$, with cutout handles on each side, utilizing any comfortable self-selected posture, that is the posture which “felt most comfortable” to him with the only stipulation being that his feet remained stationary and symmetrically placed throughout duration of the individual lift. The lifting task consisted of lifting the load from the floor to the platform of a lowering apparatus, which was positioned such that the lift was from floor to a 76cm platform. Hands were 81cm above floor level at completion of the lift cycle. The task consisted of lifting only and no manual lowering was required. The design of the lowering apparatus was such that once the load was placed on the platform and released, the platform swiveled about a hinged axis, delivering the load to a sliding board, which returned the load to its original location at floor level. The platform then automatically returned to its original horizontal position. The setup of the lifting task is seen in Figure 3.1.

3.2.1.2 Session I – Determining the Mass of the Load

The mass of the load lifted by each participant was determined utilizing the psychophysical approach as described in the literature (Aghazadeh and Ayoub, 1985; Lu and Aghazadeh, 1994; Ciriello et al., 1990; Garg and Saxena, 1979; Snook et al., 1970). The duration of the first lifting session was 20 minutes. At the beginning of session I, the wooden box was empty, providing a mass of 4.3kg . The participant was instructed to lift the box from the floor to the platform of the lowering apparatus once every 15 seconds as prompted by the digital voice recording. Throughout this session, the participant was encouraged to adjust the mass of the load by adding (or subsequently removing) metal

pieces of various undisclosed masses, until he felt that the mass of the load was equivalent to the maximum that he could continuously lift at a rate of 4 lifts per minute for an 8-hour work period without becoming overheated, unusually tired, and or weakened. The resulting mass was recorded and used as the functional mass. Once this functional mass was determined, the participant continued to perform the lifting task until the session duration of 20 minutes expired. Also, during this session, the anthropometric measurements of stature and weight were made.

Figure 3.1 Experimental task setup (adapted from Kim, 1992)

3.2.1.3 Session II –Repetitive Lifting Session

The repetitive lifting session was performed subsequent to the determining of the mass of the load on a day other than the day session I was performed. There was usually

a 3 to 5 day period between the experimental sessions. Each repetitive lifting session consisted of five (5) discrete parts: camera system calibration, participant preparation, EMG amplifier adjustment and Eva data capture software program setup, strength testing and subjective fatigue analysis, and repetitive lifting task performance. Additionally, for the purpose of qualitative analyses of subject lifting techniques, each lifting session was videotaped from a sagittal view of the participant's left side. This video was used to assist in the interpretation and visual verification of the quantitative results. The setup for experimental session II can be observed in Figure 3.2.

Figure 3.2 Experimental session II equipment configuration layout

3.2.1.3.1 Camera System Calibration

Prior to the arrival of the participant in each experimental session II, it was necessary to calibrate the camera system for accurate digital data collection. The COHU[®] (San Diego, CA) High Performance CCD Chip 6600 series digital camera was situated on a tripod, such that the direction of movement of the lifting task was perpendicular to the long axis of the camera and the area of calibration covered the entire area of session II kinematic data capture. The protocol for camera system calibration was as follows.

1. Turn on computers
 - a. IBM PC 300 host computer
 - b. MIDAS (Motion Engineering Company, Indianapolis, IN) motion analysis computer
2. Open Expert Vision HiRES Eva 6.0 (Motion Analysis Corporation, San Diego, CA) program on host computer and load current project
3. Turn on digital camera
4. Adjust position of camera such that total desired area of data capture is in view
5. Place calibration cube in area of kinematic data capture and ensure that reflective markers on cube are visible on MIDAS computer screen
6. Set Eva program to acquire cube calibration data
7. Ensure that there are no unwanted images on the MIDAS computer screen and that the threshold is set to yield good images; adjust if necessary
8. Set frame rate to 60 frames per second and duration to 3 seconds

9. Collect cube calibration data and save as .vcl file
10. Load .vcl file to Eva program and identify the markers on the calibration cube
11. Calibrate data capture area and ensure the “goodness of fit” (GOF) value is below 1
12. Complete and save calibration project

3.2.1.3.2 Participant Preparation

Prior to performing the repetitive lifting task, each participant was instrumented with a Polar (Polar Electro Inc., Woodbury, NY) Beat[®] Model 77048 digital heart rate monitor with T31 transmitter and continuous remote wristwatch display, and with bipolar surface electrodes at sites representing the activity of thoracic and lumbar erector spinae on both the left and right sides and the left and right vastus lateralis muscles. At all electrode placement sites, the skin was prepared by cleaning and gently abrading the area with alcohol prep pads. The electrode pairs were designed in a single housing, such that there was a constant predetermined sensor spacing of 18mm with dual medical grade stainless steel reference pads. The configuration was positioned over the muscle group such that the inter-electrode center-to-center space was parallel to the fiber orientation of the muscle group to be monitored and placed as follows:

- 1) **Lumbar erector spinae:** Electrode pairs were placed approximately 3 cm lateral to the posterior spinous process at the level of L3 on both left and right sides.
- 2) **Thoracic erector spinae:** Electrode pairs were placed approximately 4 cm lateral to the posterior spinous process at the level of T9 on both left and right sides.

- 3) **Vastus lateralis:** Electrode pairs were placed over the prominent extrusion of the muscle belly between the hip and the patella.

Figure 3.3 Configuration of EMG electrode pair placement. (1) lumbar erector spinae, (2) thoracic erector spinae, (3) vastii lateralis muscle groups (adapted from Chaffin *et al.*, 1999)

Configuration of electrode pair placement can be seen in Figure 3.3.

Each participant was also instrumented with spherical reflective markers, placed at the following locations on the left side of his body, which can be seen in Figure 3.4.

- 1) Fifth metatarsophalangeal joint
- 2) Lateral malleolus (ankle joint)
- 3) Lateral epicondyle of the femur (knee joint)
- 4) Greater trochanter (hip joint)
- 5) L5/S1 disc (mid-waist)
- 6) Posterior spinous process of the T1 vertebra

- 7) Gleno humeral joint (shoulder)
- 8) Lateral epicondyle of the humerus (elbow joint)
- 9) Ulnar styloid (wrist joint)
- 10) One flat circular reflective marker was also located on the x-center of the 46cm x 30cm x 16cm load to be used during the lifting task, with the lowest point of the marker flush to the bottom of the box.

Figure 3.4 Configuration of marker placement (adapted from Chaffin et al., 1999)

3.2.1.3.3 EMG Amplifier Adjustment and Eva Setup

Once the participant was instrumented, it was necessary to adjust the gain of the analog Motion Lab Systems (Baton Rouge, LA) MA-300-16[®] EMG system pre-amplifier of each channel to retain the recorded EMG signal at the greatest resolution available without losing any signal to clipping. The MA-300-16[®] EMG system digital data transmission module, including active EMG electrodes and pre-amplifiers was attached to a belt which was placed around the participant, just above waist level, and was situated on the participant's lower back. Six (6) channels were used to collect and amplify the EMG signal, one representing each muscle group observed. Each pre-amplifier for each channel possessed a knob which could be adjusted to integer values from 0 to 9, each number representing 400, 2000, 4000, 5700, 8000, 10000, 11500, 13200, 16600, and 20000 times amplification on that channel, respectively. EMG and kinematic/video data collection were automatically synchronized. The protocol of amplifier adjustment and program setup was as follows.

1. Insert cable to digital data transmission module, connecting module to MA-300-16[®] EMG system desktop unit and Eva program
2. In Video Setup screen
 - a. Change collection mode of current project in Eva program from "Cube Calibration" to "Trial Data"
 - b. Ensure that frame rate is set to 60 frames per second and set duration to 5 seconds
3. Switch to Analog Setup screen and adjust collection rate to 960 Hz

4. Select channels 0 through 5 to be used and input range from –5V to 5V for each channel selected
5. Instruct participant to perform lifting task while analog data is collected in order of
 - a. Start data collection
 - b. Prompt participant to lift load
 - c. Participant performs lifting task
6. Visually inspect graphs of analog data collected to ensure signal is detected, with no clipping and with enough room for expected EMG amplitude increase
7. Adjust amplification on channels not exhibiting attributes stated in step 6
8. Repeat steps 5 through 7 until signals on all channels exhibit attributes stated in step 6

3.2.1.3.4 Strength Testing and Subjective Fatigue Analysis

Once the equipment was fully calibrated and setup for the experimental session, each participant performed a battery consisting of two initial (rested) strength tests and a self-rated subjective fatigue assessment in the following order:

1. Seated rest period of five (5) minutes,
2. Subjective fatigue analysis self-rating utilizing test instrument, which can be viewed in Appendix B, adapted from Mendoza *et al.*, 1999,
3. Static composite strength test as described by Jackson (1999), using the ST1 Force Monitor (Dynadex Corp, Ann Arbor, MI) and strain gauge load cell,
4. Seated rest period of five (5) minutes,

5. Dynamic leg lift floor to knuckle height strength test using dynamic strength testing method described by Aghazadeh (1986), using the MSR 500X Mini-Gym (Cleveland, OH) and digital dynamometer.

3.2.1.3.5 Repetitive Lifting Task

Following the strength testing, each participant performed the repetitive lifting task described in section 3.2.1.1 for a period of 2 hours, utilizing the load, which was psychophysically determined in session I. The 2-hour period was divided into eight (8) fifteen-minute periods. Throughout the fourteenth and fifteenth minutes of each of the fifteen-minute periods, the electromyographic (EMG) activity of the monitored muscles, as well as the kinematic data was synchronously recorded. Immediately following each fifteen-minute period, subjective fatigue analysis self-rating and dynamic leg lift floor to knuckle height strength test were performed as was done immediately before the beginning of the repetitive lifting task such that there was as short a time period between lifting bouts as possible. Immediately following the 2-hour lifting period, strength testing and subjective fatigue analysis were performed as indicated in steps 2 through 5 of section 3.2.1.3.4.

3.2.2 Methods of Data Collection

During experimental session II, five types of data were acquired. These were static composite strength, dynamic leglift floor to knuckle height strength, subjective fatigue, kinematic and EMG data. This section describes the specifics of the data collection.

3.2.2.1 Static Composite Strength

Static composite strength measurements were collected immediately prior to and immediately after the performance of the 2-hour lifting session as described by Jackson (1999). The protocol of the testing was as follows.

1. Connect and secure the short handle (grip width of 17.25cm) to the load cell of the ST-1 Force Monitor
2. Adjust height of force monitor bar such that handle is 43.2cm ($\approx$ 17in.) above the platform
3. Power on the digital display apparatus of the ST-1 Force Monitor and calibrate (zero) the unit such that the digital display reads “0” when no tensile force is applied to the handle
4. Set display knob to PEAK and reset knob to TEST
5. Instruct participant to assume test position as follows:
 - a. Stand on platform with feet centered lengthwise directly beneath the handle and spread a comfortable distance apart
 - b. Grip the handle (palms facing each other) and bend knees, with handle between legs and arms as close to the body as possible, without touching legs with arms
 - c. Hold head up (looking directly forward) to assume correct position
6. Once participant is in correct test position, instruct him to exert maximum force with legs by not jerking, but applying force in a “consistent, forceful manner” giving him the following instructions:

- a. “Grip the handle and exert force with your legs.”
 - b. “Keep your arms next to your body. Your arms should be touching your body.”
 - c. “Apply a steady, forceful effort until instructed to stop, after three (3) seconds.”
 - d. “Are there any questions?”
7. Answer any questions then instruct participant to try a first attempt at half effort to physically familiarize him with the test protocol
8. Perform strength test
 - a. Instruct participant to exert force as described in step 6
 - b. Begin stopwatch 3-second countdown
 - c. Instruct participant to stop at end of three seconds
 - d. Record maximum force readout from display
 - e. Set display knob to RESET then back to TEST
9. Instruct participant to rest in seated position for two (2) minutes
10. Repeat steps 8 and 9, no more than six (6) times, until three (3) values are obtained that are within 10% of one another
11. Take the average of the three nearest values and record that score as the average static composite strength

3.2.2.2 Dynamic Leglift Floor to Knuckle Height Strength

Dynamic leglift floor to knuckle height strength measurements were collected immediately prior to and immediately after the performance of the 2-hour lifting session,

as well as between each of the 15-minute lifting bouts as described by Aghazadeh (1986).

The protocol of the testing was as follows.

1. Connect and secure the long handle (grip width of 46cm, similar to box used in lifting task) to the load cell attached to the MSR 500X Mini-Gym and assure isokinetic dynamometer is set to yield maximum resistance and a lifting speed of approximately 75 cm per second
2. Adjust initial length of the Mini-Gym cord such that handle is 43.2cm (≈ 17 in.) above the platform
3. Power on the digital display apparatus of the load cell and calibrate (zero) the unit such that the digital display reads “0” when no tensile force is applied to the handle
4. Set display knob to PEAK and reset knob to TEST
5. Instruct participant to assume test position as follows:
 - a. Stand on platform with feet centered lengthwise directly beneath the handle and spread a comfortable distance apart
 - b. Grip the handle (palms facing each other) and bend knees, with forward flexion of the back to an absolute minimum, such that he is in a full squat position with handle directly in front of legs and arms as close to the body as possible, without touching legs with arms or handle
 - c. Hold head up (looking directly forward) to assume correct position

- d. Once participant is in correct test position, instruct him to lift the handle vertically as fast as possible in a stable position in a “consistent, forceful manner” throughout the range of the lift until he is standing fully erect, with arms remaining straight and close to his body throughout the lifting motion
6. Answer any questions then instruct participant to try a first attempt at half effort to physically familiarize him with the test protocol
7. Perform strength test
 - a. Instruct participant to exert lifting force as described in step 5
 - b. Record maximum force readout from display
 - c. Set display knob to RESET then back to TEST
8. Instruct participant to rest in seated position for two (2) minutes
9. Repeat steps 7 and 8, no more than six (6) times, until three (3) values are obtained that are within 10% of one another
10. Take the average of the three nearest values and record that score as the average dynamic leglift floor to knuckle height strength

3.2.2.3 Subjective Fatigue

Subjective fatigue self-rating was collected as measure or direct indicator of how “tired” or weakened the subject felt throughout the course of the experiment. The instrument used in the current study is referred to as the “subjective fatigue rating scale.” Each individual numerical level on the subjective fatigue rating scale is referred to as the subjective fatigue rating.

The test instrument used to collect and record participant subjective fatigue rating can be viewed in Appendix B. The subjective fatigue rating scale is adapted from the Brief Fatigue Inventory (BFI) developed by researchers at the University of Texas M.D. Anderson Cancer Center. The Brief Fatigue Inventory form can be seen in Appendix C. The BFI is a brief, simple, and easy to use tool developed for the rapid assessment of severity of fatigue in both clinical and research settings (Mendoza et *al.*, 1999). The BFI was developed for use in the assessment of fatigue in cancer patients, to determine the severity of fatigue and the effect of fatigue on their everyday functioning. The complete BFI consists of nine (9) items of equal weight, which are questions with numerical ratings of value zero (0) to ten (10). Mendoza et *al.* found the BFI to be very reliable, with a Chronbach's alpha reliability ranging from 0.82 to 0.97, and found that the BFI correlated well with similar, but more complicated measures of fatigue.

The subjective fatigue rating scale used in the current study was adapted from question 1 of the BFI, which reads "Please rate your fatigue (weariness, tiredness) by selecting the one number that best describes your fatigue right NOW." The associated rating scale to question 1 of the BFI is given as zero (0) to ten (10), with the extremes being labeled as "no fatigue" at the minimum and "as bad as you can imagine" at the maximum. The overall scoring (brief inventory index) of the BFI is interpreted, with high reliability, as seen in Table 3.2.

The subjective fatigue rating scale directed the participant to "Please indicate the level of fatigue you are currently experiencing, using the following scale, by placing an 'X' in the appropriate box," with numerical levels given from zero (0) to ten (10). The

interpretation of individual numerical levels of fatigue was also included in the instrument as indicated in Table 3.3.

Table 3.2 Numerical interpretation of the Brief Fatigue Inventory
(Mendoza et al., 1999)

Brief Inventory Index	Level of Fatigue
0	None
1 to 3 (or 4)	Mild
4 (or 5) to 6	Moderate
7 to 10	Severe

Table 3.3 Numerical Interpretation of Subjective Fatigue Rating Instrument

Subjective Fatigue Rating	Level of Fatigue
0	Not at all
1 to 3	Mild fatigue
4 to 6	Moderate fatigue
7 to 9	Severe fatigue
10	Unable to continue

3.2.2.4 Kinematic Data

Kinematic data were collected in intervals described in section 3.2.1.3.5. Five (5) seconds of kinematic data were recorded individually for eight (8) lift cycles during the fourteenth and fifteenth minutes of each fifteen-minute lifting period of the two-hour experimental session II. Marker position data were collected through the COHU[®] High Performance CCD Chip 6600 series digital camera at 60 Hz and transmitted to MIDAS computer, then transferred directly to the Eva 6.0 program on the host IBM PC300 computer. In the Eva 6.0 program, kinematic data were initially recorded and stored as separate .vc1 files for each lift cycle. Once the data files were saved, the individual

marker position data within each file were manually tracked within the Eva 6.0 program to ensure correct marker detection and identification. Once tracked, the data were low-pass filtered at 6-Hz, using a 4th order, zero-lag Butterworth filter and each file was then saved as a .trc file, containing smoothed position data for each marker.

Figure 3.5 Eight-segment biomechanical model used to calculate kinematic and force parameters

In order to extract kinematic variables of interest, an 8-segment (foot, shank, upper leg, pelvis, head-neck-upper trunk, upper arm, forearm, and load-hand), with an additional measurement of lumbosacral angle, fully dynamic biomechanical model using a 7.5cm (McGill and Norman, 1987; Leskinen et al., 1992) single-arm muscle equivalent was used. The model used in the current study, which can be observed in Figure 3.5, was similar to dynamic biomechanical models described by McGill and Norman (1985), Chaffin et al. (1999), Straker (1994), de Looze et al. (1993), and Sparto et al. (1997). Segment mass data were obtained from Webb Associates (1978); and inertial data were obtained from Plagenhoef et al. (1983) and Dempster (1955). Mass of the load lifted,

mass of participant, and kinematic (marker position) data obtained from previously saved .trc files were also used as inputs to the model to determine parameters of interest. A program was written using SPSS SigmaPlot 2001 for Windows Version 7.101 software, specifically to extract parameters of interest from the kinematic data in the current experiment. The kinematic program can be viewed in Appendix D. The parameters of interest which were calculated as the ultimate output of the kinematic program were duration of the lift (Duration), peak vertical load acceleration (PeakVertAcc), average force on hands (HandForce), peak trunk flexion angle (PeakFlex), peak trunk extension velocity (PeakExtVel), peak shear force at L5/S1 joint (PeakShear), peak compression force at L5/S1 joint (PeakCom), peak moment at L5/S1 joint (PeakMom), Integrated moment at L5/S1 joint (Imoment), trunk flexion angle at initiation of lift (Flx), and knee angle at initiation of lift (Knee). These parameters were first calculated for each individual lift cycle, then the average value of the eight (8) lift cycles at a given time during the experimental session was calculated for each parameter and returned as the reported output. To obtain these parameters, kinematic data from the eight (8) .trc files for a given time were imported into a single SigmaPlot spreadsheet. The resultant data were processed and the parameters of interest for each individual lift cycle were determined in the following steps:

3.2.2.4.1 Determining Initiation and End of Lift

For each lift observed, it was first necessary to determine the beginning and end of the lift so that only the data considered to be within the lift cycle could be analyzed. The lift cycle was considered to begin at the time when load began to move in the positive y (vertically upwards) direction. This was indicated by a positive change in the y

direction of the position of the marker located on the load. The end of the lift was considered to occur at the time when the participant released the load from his hand. That event was indicated by a progressive positive change in both the x and y directions in the positional difference of the marker located on the load and the marker located on the wrist joint of the participant. The data collected within the temporal confines of the events described here were considered as belonging to a discrete lift cycle and were thus analyzed. The time difference between these events was calculated and recorded as the duration of the lift.

3.2.2.4.2 Calculation of Kinematic Variables

Once the lift cycle was defined, it was possible to calculate the kinematic variables peak vertical load acceleration (PeakVertAcc), peak trunk flexion angle (PeakFlex), peak trunk extension velocity (PeakExtVel), trunk flexion angle at initiation of lift (Flx), and knee angle at initiation of lift (Knee). In this stage, angles, angular velocities, and angular accelerations of the hand-load, lower arm, upper arm, and trunk were determined, with respect to the horizontal (x-axis), as well as segment center of mass (COM) position and location and segment radius of gyration position were calculated for use in calculating kinetic parameters later in the analysis.

- Peak vertical load acceleration (PeakVertAcc) was calculated using double-differentiation of the position data in the positive y-direction of the load. This was performed using equation 3.1. The value is expressed in meters per second².

$$PeakVertAcc = Max(\frac{d^2 y_{load_i}}{dt^2}) = Max(\frac{y_{load_{i+1}} + y_{load_{i-1}} - (2y_{load_i})}{t^2}), \quad (3.1)$$

where y_{load} = linear vertical position of marker on load,

t = time between frames of data (1/60),

i = frame of data

- Peak trunk flexion angle (PeakFlex) was defined as the maximum angle (degrees) of flexion from the vertical (y-axis) of the lumbosacral joint. PeakFlex was calculated using equations 3.2a, 3.2b and 3.3.

$$TrunkFlexionAngle_i = (90 + \tan^{-1}(\frac{y_{l5_i} - y_{tl_i}}{x_{l5_i} - x_{tl_i}})), \quad \text{if } x_{l5} \geq x_{tl} \quad (3.2a)$$

$$TrunkFlexionAngle_i = (90 - \tan^{-1}(\frac{y_{l5_i} - y_{tl_i}}{x_{l5_i} - x_{tl_i}})), \quad \text{if } x_{l5} < x_{tl} \quad (3.2b)$$

$$PeakFlex = \text{Max}(Trunk Flexion Angle_i), \quad (3.3)$$

where i = frame of data

- Peak trunk extension velocity (PeakExtVel) was an angular velocity, expressed in degrees per second and was calculated using equations 3.4a, 3.4b, 3.4c, and 3.5, derived from Winter (1990).

For $i = 1$ to k ,

$$TrunkExtensionVelocity = \frac{-\theta_{l5_{i+2}} + 4\theta_{l5_{i+1}} - 3\theta_{l5_i}}{2t}, \quad 1 \leq i \leq 2 \quad (3.4a)$$

$$TrunkExtensionVelocity = \frac{\theta_{l5_{i+2}} + 8\theta_{l5_{i+1}} - 8\theta_{l5_{i-1}} - \theta_{l5_{i-2}}}{12t}, \quad 3 \leq i \leq k-2 \quad (3.4b)$$

$$TrunkExtensionVelocity = \frac{3\theta_{l5_i} - 4\theta_{l5_{i-1}} + \theta_{l5_{i-2}}}{2t}, \quad k-1 \leq i \leq k \quad (3.4c)$$

$$PeakExtVel = \text{Max}(TrunkExtensionVelocity) \quad (3.5)$$

where i = frame of data,

k = total number of frames analyzed,

θ_{l5} = TrunkFlexionAngle,

t = time between frames of data (1/60)

- Trunk flexion angle at initiation of lift (Flx) was defined as the angle (degrees) of flexion from the vertical (y-axis) of the lumbosacral joint at the initiation of the lift (frame 1 of analyzed data). Flx was calculated using equations 3.6a and 3.6b.

$$Flx = 90 + \tan^{-1}\left(\frac{y_{l5_1} - y_{t1_1}}{x_{l5_1} - x_{t1_1}}\right), \quad \text{if } x_{l5} \geq x_{t1} \quad (3.6a)$$

$$Flx = 90 - \tan^{-1}\left(\frac{y_{l5_1} - y_{t1_1}}{x_{l5_1} - x_{t1_1}}\right), \quad \text{if } x_{l5} < x_{t1} \quad (3.6b)$$

- Knee angle at initiation of lift (Knee) was defined as the included angle between the shank and upper leg segments at the initiation of the lift (frame 1 of analyzed data). Knee was calculated using equations 3.7a and 3.7b.

$$Knee = \tan^{-1}\left(\frac{y_{knee_1} - y_{ankle1_1}}{x_{ankle1_1} - x_{knee_1}}\right) + \tan^{-1}\left(\frac{y_{hip_1} - y_{knee_1}}{x_{hip_1} - x_{knee_1}}\right), \quad \text{if } x_{knee} \geq x_{hip} \quad (3.7a)$$

$$Knee = 180 + \left| \tan^{-1}\left(\frac{y_{knee_1} - y_{ankle1_1}}{x_{ankle1_1} - x_{knee_1}}\right) + \tan^{-1}\left(\frac{y_{hip_1} - y_{knee_1}}{x_{hip_1} - x_{knee_1}}\right) \right|, \quad \text{if } x_{knee} < x_{hip} \quad (3.7b)$$

- Segment angles, angular velocities, and angular accelerations of the hand-load, lower arm, upper arm, and trunk were determined, with respect to the horizontal (x-axis). Angular velocities and accelerations were calculated using equations 3.8-3.10, derived from Winter (1990).

❖ Segment Angles

$$\theta_{segment_i} = 180 - \tan^{-1}\left(\frac{y_{distal_i} - y_{proximal_i}}{x_{distal_i} - x_{proximal_i}}\right), \quad \text{if } y_{distal} > y_{proximal} \text{ and } x_{distal} > x_{proximal} \quad (3.8a)$$

$$\theta_{segment_i} = \tan^{-1}\left(\frac{y_{distal_i} - y_{proximal_i}}{x_{proximal_i} - x_{distal_i}}\right), \quad \text{if } y_{distal} > y_{proximal} \text{ and } x_{distal} < x_{proximal} \quad (3.8b)$$

$$\theta_{segment_i} = 180 - \tan^{-1}\left(\frac{y_{proximal_i} - y_{distal_i}}{x_{distal_i} - x_{proximal_i}}\right), \quad \text{if } y_{distal} < y_{proximal} \text{ and } x_{distal} > x_{proximal} \quad (3.8c)$$

$$\theta_{segment_i} = \tan^{-1}\left(\frac{y_{proximal_i} - y_{distal_i}}{x_{proximal_i} - x_{distal_i}}\right), \quad \text{if } y_{distal} < y_{proximal} \text{ and } x_{distal} < x_{proximal} \quad (3.8d)$$

where $\theta_{segment}$ = angle of segment measured from horizontal,

i = frame of data,

y_{distal} = vertical position of distal end of segment,

$y_{proximal}$ = vertical position of proximal end of segment,

x_{distal} = horizontal position of distal end of segment,

$x_{proximal}$ = horizontal position of proximal end of segment

❖ Segment Angular Velocities

For $i = 1$ to k ,

$$\omega_{segment_i} = \frac{-\theta_{segment_{i+2}} + 4\theta_{segment_{i+1}} - 3\theta_{segment_i}}{2t}, \quad 1 \leq i \leq 2 \quad (3.9a)$$

$$\omega_{segment_i} = \frac{\theta_{segment_{i+2}} + 8\theta_{segment_{i+1}} - 8\theta_{segment_{i-1}} - \theta_{segment_{i-2}}}{12t}, \quad 3 \leq i \leq k-2 \quad (3.9b)$$

$$\omega_{segment_i} = \frac{3\theta_{segment_i} - 4\theta_{segment_{i-1}} + \theta_{segment_{i-2}}}{2t}, \quad k-1 \leq i \leq k \quad (3.9c)$$

where i = frame of data,

k = total number of frames analyzed,

$\omega_{segment}$ = angular velocity of segment,

$\theta_{segment}$ = angle of segment measured from horizontal,

t = time between frames of data (1/60)

❖ Segment Angular Accelerations

For $i = 1$ to k ,

$$\alpha_{segment_i} = \frac{-\omega_{segment_{i+2}} + 4\omega_{segment_{i+1}} - 3\omega_{segment_i}}{2t}, \quad 1 \leq i \leq 2 \quad (3.10a)$$

$$\alpha_{segment_i} = \frac{\omega_{segment_{i+2}} + 8\omega_{segment_{i+1}} - 8\omega_{segment_{i-1}} - \omega_{segment_{i-2}}}{12t}, \quad 3 \leq i \leq k-2 \quad (3.10b)$$

$$\alpha_{segment_i} = \frac{3\omega_{segment_i} - 4\omega_{segment_{i-1}} + \omega_{segment_{i-2}}}{2t}, \quad k-1 \leq i \leq k \quad (3.10c)$$

where i = frame of data,

k = total number of frames analyzed,

$\alpha_{segment}$ = angular acceleration of segment,

$\omega_{segment}$ = angular velocity of segment,

t = time between frames of data (1/60)

- Positions of the hand-load, lower arm, upper arm, and trunk segment centers of mass (COM) and radii of gyration (ROG) were calculated using data obtained from Dempster (1955) and Plagenhoef et al. (1983), respectively. Linear accelerations of segment COM were calculated using equations 3.11-3.18, derived from Winters (1990).

$$COM_i = d_{COM} (\sqrt{(x_{proximal_i} - x_{distal_i})^2 + (y_{proximal_i} - y_{distal_i})^2}), \quad (3.11)$$

$$ROG_i = d_{ROG} (\sqrt{(x_{proximal_i} - x_{distal_i})^2 + (y_{proximal_i} - y_{distal_i})^2}), \quad (3.12)$$

$$x_{COM_i} = x_{proximal_i} + (COM_{segment_i})(\cos \theta_{segment_i}), \quad x_{distal} \geq x_{proximal}, \quad (3.13a)$$

$$x_{COM_i} = x_{proximal_i} - (COM_{segment_i})(\cos \theta_{segment_i}), \quad x_{distal} < x_{proximal}, \quad (3.13b)$$

$$y_{COM_i} = y_{proximal_i} + (COM_{segment_i})(\sin \theta_{segment_i}), \quad y_{distal} \geq y_{proximal}, \quad (3.14a)$$

$$y_{COM_i} = y_{proximal_i} - (COM_{segment_i})(\sin \theta_{segment_i}), \quad y_{distal} < y_{proximal}, \quad (3.14b)$$

$$a_{x_{COM}} = \frac{x_{COM_{i+1}} + x_{COM_{i-1}} - (2x_{COM_i})}{t^2}, \quad (3.15)$$

$$a_{y_{COM}} = \frac{y_{COM_{i+1}} + y_{COM_{i-1}} - (2y_{COM_i})}{t^2}, \quad (3.16)$$

$$x_{ROG_i} = x_{proximal_i} + (ROG_{segment_i})(\cos \theta_{segment_i}), \quad x_{distal} \geq x_{proximal}, \quad (3.17a)$$

$$x_{ROG_i} = x_{proximal_i} - (ROG_{segment_i})(\cos \theta_{segment_i}), \quad x_{distal} < x_{proximal}, \quad (3.17b)$$

$$y_{ROG_i} = y_{proximal_i} + (ROG_{segment_i})(\sin \theta_{segment_i}), \quad y_{distal} \geq y_{proximal}, \quad (3.18a)$$

$$y_{ROG_i} = y_{proximal_i} - (ROG_{segment_i})(\sin \theta_{segment_i}), \quad y_{distal} < y_{proximal}, \quad (3.18b)$$

where i = frame of data,

COM = linear distance of segment center of mass from proximal end of segment,

d_{COM} = distance of COM from proximal end of segment as percentage of segment length,

ROG = linear distance of segment radius of gyration from proximal end of segment,

d_{ROG} = distance of ROG from proximal end of segment as percentage of segment length,

y_{COM} = vertical position of center of mass of segment,

x_{COM} = horizontal position of center of mass of segment,

y_{ROG} = vertical position of radius of gyration of segment,

x_{ROG} = horizontal position of radius of gyration of segment,

y_{distal} = vertical position of distal end of segment,

$y_{proximal}$ = vertical position of proximal end of segment,

x_{distal} = horizontal position of distal end of segment,

$x_{proximal}$ = horizontal position of proximal end of segment,

a_{xCOM} = horizontal acceleration of center of mass of segment,

a_{yCOM} = vertical acceleration of center of mass of segment,

t = time between frames of data (1/60)

3.2.2.4.3 Calculation of Kinetic Variables

With the kinematic variables calculated, it was possible to calculate the kinetic parameters of interest. The kinetic variables to be calculated at this stage were average force (HandForce) on the hands during the lift; peak lumbosacral shear force (PeakShear), compressive force (PeakCom), and moment (PeakMom); and integrated lumbosacral moment (Imoment) over the course of the lift.

- The average force acting on the hands was calculated using equations 3.19a, 3.19b, and 3.20.

$$HandForce = load(\sqrt{(g + a_{load_y})^2 + (a_{load_x})^2}), \quad y_i \leq y_{i+1}, \quad (3.19a)$$

$$HandForce = load(\sqrt{(g - a_{load_y})^2 + (a_{load_x})^2}), \quad y_i > y_{i+1}, \quad (3.19b)$$

$$\text{Average Hand Force} = \frac{\text{HandForce}}{T} \quad (3.20)$$

where load = mass of load lifted (kg),

g = gravitational acceleration (9.81 m/s²),

a_{load_y} = vertical linear acceleration of load,

a_{load_x} = horizontal linear acceleration of load,

i = frame of data,

T = duration of lift cycle (s)

- Moments and reaction forces were calculated for each joint, from the wrist to the lumbosacral joint in handward to footward direction until the lumbosacral

moment was calculated. For joint j, moment and reaction forces were calculated in the following manner, as derived from Chaffin et al. (1999).

$$R_{j_{y_i}} = m_{segment}g + m_{segment}a_{y_{COM_i}} + R_{(j-1)_{y_i}}, \quad (3.21)$$

$$R_{j_{x_i}} = m_{segment}a_{x_{COM_i}} + R_{(j-1)_{x_i}}, \quad (3.22)$$

$$SL = \sqrt{(x_{proximal_i} - x_{distal_i})^2 + (y_{proximal_i} - y_{distal_i})^2}, \quad (3.23)$$

$$\begin{aligned} M_{ji} = & M_{(j-1)_i} + (d_{COM})(SL)(\cos \theta_{segment_i})(m_{segment})(g + a_{y_{COM_i}}) \\ & + (d_{COM})(SL)(\sin \theta_{segment_i})(m_{segment})(a_{x_{COM_i}}) + (SL)(\cos \theta_{segment_i})(R_{(j-1)_{y_i}}) \\ & + (SL)(\sin \theta_{segment_i})(R_{(j-1)_{x_i}}) + (d_{COM})(SL)(m_{segment})(\alpha_{segment_i}), \end{aligned} \quad (3.24)$$

$$PeakMom = \text{Max}(M_{j_i}), \quad (3.25)$$

$$IMoment_{t5/s1} = \sum_{i=1}^{i=T} M_{t5/s1_i}, \quad (3.26)$$

where R_{jy} = reaction force in the vertical (y) direction at joint j,

$R_{(j-1)y}$ = reaction force in the vertical (y) direction at the adjacent handward joint (j-1),

R_{jx} = reaction force in the horizontal (x) direction at joint j,

$R_{(j-1)x}$ = reaction force in the horizontal (x) direction at the adjacent handward joint (j-1),

$m_{segment}$ = mass of segment adjacent to joint j in handward direction,

a_{yCOM} = vertical acceleration of center of mass of segment,

a_{xCOM} = horizontal acceleration of center of mass of segment,

g = gravitational acceleration (9.81 m/s²),

SL = length of segment,

y_{distal} = vertical position of distal end of segment,

$y_{proximal}$ = vertical position of proximal end of segment,

x_{distal} = horizontal position of distal end of segment,

x_{proximal} = horizontal position of proximal end of segment,

M_j = is the moment at joint j,

$M_{(j-1)}$ = moment at the adjacent handward joint (j-1),

d_{COM} = distance of COM from proximal end of segment as percentage of segment length,

θ_{segment} = angle of segment measured from horizontal,

α_{segment} = angular acceleration of segment,

PeakMom_{l5/s1} = peak moment acting on the lumbosacral joint during the lift,

Imoment_{l5/s1} = integrated moment acting on the lumbosacral joint over the course of the lift,

i = frame of data

- Compressive and shear forces acting on the lumbosacral joint were calculated using equations 3.27-3.30, derived from Straker (1994). A 7cm moment arm was used to represent the musculature of the lower back acting on the forces at the lumbosacral joint.

$$F_{\text{comp}_i} = \left(\frac{M_{l5/s1_i}}{0.075} \right) + (\cos \theta_{\text{trunk}_i})(R_{l5/s1_{x_i}}) + (\sin \theta_{\text{trunk}_i})(R_{l5/s1_{y_i}}), \quad (3.27)$$

$$\text{PeakCom} = \text{Max}(F_{\text{comp}_i}), \quad (3.28)$$

$$F_{\text{shear}_i} = (\sin \theta_{\text{trunk}_i})(R_{l5/s1_{x_i}}) + (\cos \theta_{\text{trunk}_i})(R_{l5/s1_{y_i}}), \quad (3.29)$$

$$\text{PeakShear} = \text{Max}(F_{\text{shear}_i}), \quad (3.30)$$

where F_{comp} = compressive force acting on lumbosacral joint,

$M_{l5/s1}$ = moment acting on lumbosacral joint,

θ_{trunk} = angle of trunk measured from horizontal at l5/s1 joint,

$R_{l5/s1y}$ = reaction force in the vertical (y) direction at l5/s1 joint,

$R_{l5/s1x}$ = reaction force in the horizontal (x) direction at l5/s1 joint,

PeakCom = peak compressive force acting on the lumbosacral joint during the lift,

F_{shear} = shear force acting on lumbosacral joint,

PeakShear = peak shear force acting on the lumbosacral joint during the lift

3.2.2.4.4 EMG Data

EMG data were collected synchronously with kinematic data in intervals described in section 3.2.1.3.5. Five (5) seconds of EMG data were recorded individually for eight (8) lift cycles during the fourteenth and fifteenth minutes of each fifteen-minute lifting period of the two-hour experimental session II. The EMG activity of each muscle was detected and processed by respective double-differential pre-amplifier active electrodes, with gain up to 20000, a common mode rejection ratio of 100 dB, input impedance of greater than 10^8 ohms, noise of less than 1.2 uV RMS, and a frequency pass-band of 20Hz-2000 Hz. The analog signal was sampled via a 16-bit data acquisition card at a rate of 960 samples per second and stored for further processing as .anc files.

A program was written using SPSS SigmaPlot 2001 for Windows Version 7.101 software, specifically to extract parameters of interest from the EMG data in the current experiment. The program that was formulated can be viewed in Appendix E. The specific parameters extracted from the EMG data for each muscle group observed were (a) normalized maximum mean absolute value (MAV) over the course of the lift cycle and (b) EMG normalized median frequency (MDF) observed during the course of the lift. Analysis of variance (ANOVA) was performed on the EMG data to determine any effect of side (left or right) on the EMG parameters. As no significant effect of side was

observed, the average of the left and right sides for each muscle group of EMG parameters were averaged and reported as a single value, in accordance with Potvin (1992). To obtain these parameters, EMG data from the eight (8) .anc files for a given time and the corresponding kinematic marker location data from the eight (8) .trc files from the same time were imported into a single SigmaPlot spreadsheet. The resultant data were processed and the parameters of interest were determined as follows:

3.2.2.4.4.1 Normalized Maximum MAV Over Course of Lift Cycle

1. DC offset/bias of raw EMG on each channel was calculated and removed from signal
2. Each EMG signal was full wave rectified and linear envelope of MAV was calculated using a time constant of 240 ms
3. From each linear envelope, the maximum MAV was extracted
4. For each muscle group observed, the average of the eight (8) maximum MAVs observed at the given time was calculated and recorded as the “maximum MAV” for that muscle group, for that subject, at that time
5. For each muscle group, the maximum MAVs were normalized to the greatest maximum MAV for a given subject over the course of the experiment, such that the greatest maximum MAV was equal to 1, utilizing equation 3.31.

$$\text{Normalized Maximum MAV}_{ij} = \frac{\text{Maximum MAV}_{ij}}{\text{Max}(\text{Maximum MAV}_i)}, \quad (3.31)$$

for muscle group i at time j

3.2.2.4.4.2 Normalized Median Frequency

1. Timing of initiation and completion of lift was determined from kinematic data as described in section 3.2.2.4.1
2. For each muscle group observed, at each time, 1.33 seconds (1024 data points) of EMG data immediately following initiation of lift were analyzed, and the average MDF was determined as follows
 - a. Processing of four (4) time epochs of 0.267 seconds (256 data points) were accomplished utilizing the Fast Fourier Transform (FFT) to obtain respective power density spectra; no zero padding was performed
 - b. MDF was calculated from each epoch utilizing equation 3.32.

$$\int_0^{MDF} P(f)df = \int_{MDF}^{\infty} P(f)df, \quad (3.32)$$

where P =power and f =frequency (Hz)

- c. Average value of the MDFs of the four (4) epochs was calculated and recorded as the MDF for that muscle group, for that subject, for that lift cycle, at that time
 - d. The average of the eight (8) MDFs, represented the eight lift cycles observed at one time, of a given muscle group determined in step 2c was calculated and recorded as the MDF for that muscle group, for that subject, at that time
3. For each muscle group, the MDFs were normalized to the greatest MDF for a given subject over the course of the experiment, such that the greatest maximum MDF was equal to 1, utilizing equation 3.33.

$$\text{Normalized MDF}_{ij} = \frac{\text{MDF}_{ij}}{\text{Max}(\text{MDF}_i)}, \quad (3.33)$$

for muscle group i at time j

3.3 Statistical Protocol

The primary objective of this study was to determine any effects of progressive fatigue during a manual lifting task, where freestyle lifting technique was utilized, on several variables associated with lifting strategy. A further objective of the study was to compare and characterize several static, dynamic, and subjective parameters used to quantify levels of dynamically induced fatigue in a manual lifting task. To fulfill these objectives, the use of multivariate analysis of variance (MANOVA), (univariate) analysis of variance (ANOVA), and correlation analysis techniques, to include canonical correlation and primary factors analyses, were employed.

Four (4) hypotheses were asserted at the onset of the study. These hypotheses were:

1. That local muscle fatigue and general fatigue would be experienced by the subjects as the repetitive lifting task proceeded as indicated by (a) decreased EMG median frequency power, (b) decreased static strength, (c) decreased dynamic strength, and (d) increased subjective fatigue rating.
2. That the lifting strategies of the subjects would change as the repetitive lifting task proceeded, resulting in significant increases in (a) maximum EMG mean absolute value parameters, (b) duration of the lifting cycle, (c) knee angle at the initiation of the lift, (c) lumbar vertebral (trunk) flexion angle at the initiation of the lift, (d) peak vertical load acceleration, (e) average force on the hands, (f) peak lumbar vertebral (trunk) flexion, (g) peak lumbar vertebral extension (trunk) velocity, (h) peak shear

force at L5/S1 joint, (i) peak compression force at L5/S1 joint, (j) peak moment at L5/S1 joint, and (k) integrated moment at L5/S1 joint.

3. The onset and progression of fatigue and the variation in the kinematic and biomechanical force parameters are correlated.
4. The measured parameters of dynamically induced fatigue as measured using dynamic and static measurement techniques, as well as subjective fatigue rating are related.

3.3.1 Independent Variables

There were three (3) independent variables in the analysis. The first independent variable, “Subject,” consisted of ten (10) levels, one representing each participant of the study. The second independent variable, “Time,” consisted of nine (9) levels. These levels were designated as numerical integer values zero (0) through eight(8), each value representing a point in time that specific data were recorded during the experiment. The data were recorded at fifteen-minute intervals, from zero (0) to one hundred twenty (120) minutes, and the “real-time” minute values represented by each level can be determined by multiplying the numerical level designate (0 through 8) by fifteen. The third independent variable, “Posture,” consisted of three (3) levels, one representing each of three distinct lifting postures assumed by the participant in the performance of the lifting task. The three postures were designated as semi-squat (1), semi-stoop (2), and stoop (3) lifting postures.

3.3.2 Dependent Variables

There were twenty (20) dependent variables in the analysis. These dependent variables are listed in Table 3.4.

Table 3.4 Summary of dependent variables

1	Duration of the lift cycle
2	Peak vertical load acceleration
3	Average force on hands
4	Peak lumbar vertebral (trunk) flexion
5	Peak lumbar vertebral (trunk) extension velocity
6	Peak shear force at L5/S1 joint
7	Peak compression force at L5/S1 joint
8	Peak moment at L5/S1 joint
9	Integrated moment at L5/S1 joint
10	Dynamic leglift floor to knuckle height strength
11	Static composite strength
12	Subjective fatigue rating
13	Normalized median frequency of EMG of lumbar erector spinae (at L3-level)
14	Normalized amplitude of EMG of lumbar erector spinae (at L3-level)
15	Normalized median frequency of EMG of thoracic erector spinae (at T9-level)
16	Normalized amplitude of EMG of thoracic erector spinae (at T9-level)
17	Normalized median frequency of EMG of vastii lateralis
18	Normalized amplitude of EMG vastii lateralis
19	Knee Angle at the initiation of the lift
20	L5/S1 joint (trunk) angle at the initiation of the lift

3.3.3 Analysis of Variance Techniques: ANOVA and MANOVA

Analysis of variance (ANOVA) is a flexible and important statistical analysis tool used to determine and interpret the differences between the means of different populations. ANOVA analysis utilizes the measurements of the mean and the variance of each group to determine if their differences are statistically significant, such that a more

accurate comparison between groups can be made. Where statistically significant differences are detected between groups using ANOVA, post-hoc tests can be performed to further analyze and interpret those differences.

In the case where multiple independent variables are analyzed, the use of numerous independent ANOVA analyses can increase the risk of type I error (detecting significant differences where no differences exist). To ensure no inflation of the type I error rate as a result of numerous ANOVA analyses, multivariate analysis of variance (MANOVA) is generally performed (Everitt and Dunn, 1991; Mardia *et al.*, 1979). MANOVA is an extension of ANOVA, where analyses of several independent variables are performed simultaneously and the experiment-wise type I error rate is controlled. MANOVA is typically used as a justification or “gateway” to univariate analyses of variance (Cooley and Lohnes, 1971; Tabachnick and Fidell, 1996) and is as such a two-step process. In the first step, the overall hypothesis of no differences in the means for the different groups is tested. If the test returns a significant multivariate F-statistic (typically Wilk’s lambda), individual univariate ANOVA tests are conducted to further detect group differences. Where significant differences are detected, post-hoc tests can be performed.

Statistical analysis of the data in the current study began by performing an initial multivariate analysis of variance (MANOVA) test on the entire data set to determine any significant overall effect of the independent variables (posture selected and time) or their interaction. Wilk’s lambda was chosen as the as the MANOVA test criterion in the data analysis of the current study. Where any significant effect, at $\alpha=0.05$ -level was detected, separate analysis of variance (ANOVA) tests were applied to each independent variable.

Where any significant ($p \leq 0.05$) or marginally significant ($0.05 < p < 1$) effect of the independent variables or their interaction was detected utilizing ANOVA, least squares means (post-hoc) tests utilizing the Tukey-Kramer adjustment for multiple comparisons were performed to determine where differences existed. These functions were performed using a program in SAS v8.1 statistical software package. The complete program can be viewed in Appendix F.

3.3.4 Correlation Analysis

Correlation analysis is a term describing any of a number of statistical analysis tools used to relate two sets of variables. Two such tools often used in various disciplines are canonical correlation analysis (CCA) and principal factors analysis (PFA).

Canonical correlation analysis is a multivariate linear statistical analysis technique that is exploratory, dimensionality-reducing, and predictive in nature (Thompson, 1984). CCA is an extension of multiple regression and is used to analyze multidimensional relationships between multiple variables of two sets, frequently indicator and response variables. CCA computes a series of canonical functions that best describe the linear relationship between a linear combination of response variables and a linear combination of indicator variables. The maximum number of canonical functions between response and indicator variable sets is equal to the number of variables in the smaller of the two sets. Each function describes a distinct pattern that exists in the data. Canonical functions are determined using equation 3.34, and ranked according to the strength of the linear combination of response variables and the linear combination of indicator variables (Tabachnick and Fidell, 1996).

$$Y_1B_1 + Y_2B_2 + Y_3B_3 + \dots Y_nB_n = A_0 + X_1A_1 + X_2A_2 + X_3A_3 + \dots X_nA_n, \quad (3.34)$$

where Y = indicator variable,

B = relative weight of variable Y_n ,

A_0 = intercept of linear function,

X = response variable,

A_n = relative weight of variable X_n

Table 3.5 Summary of parameters observed in interpretation of CCA

Canonical Parameter	Description
Canonical Variate	Linear combination of a set of original variables, from which the canonical function is derived.
Pillai's Test Statistic	F-test statistic indicating likelihood of nonexistence of relationship identified between canonical variates in function.
Canonical Loading	Weights in the linear equation of variables that create the canonical variate. Describes the correlation between the original variable and the corresponding variate.
Canonical Cross Loading	Describes the correlation between the original variable and the opposite variate.

The first canonical function describes the stronger relationship and each subsequent function describes a relationship of lesser strength. In the interpretation of canonical correlation analysis, several output parameters may be observed. A description of these parameters can be seen in Table 3.5.

Principal factors analysis (PFA) is a special case of CCA, which can be used to uncover the underlying structure of a relatively large set of variables (Dunteman, 1989; Levine, 1977). Unlike the standard case of CCA, in PFA variables are not characterized

into separate groups and all variables are thereby analyzed as a single set of data. PFA seeks the least number of factors that can account for the common variance in a set of the original variables. This is done by determining a linear combination of variables, such that the maximum variation is extracted from those variables. Subsequent linear combinations, or factors, may be extracted and are ranked in the decreasing order of the variation that they explain. Equations 3.35 and 3.36 describe the general form used to determine factors in PFA.

$$Y = X_1B_1 + X_2B_2 + X_3B_3 + \dots X_nB_n, \quad (3.35)$$

where Y = characteristic or concept described by factor,

X = dimension or underlying component of factor,

B_n = relative weight of variable X_n ,

and

$$X = Z_1B_1 + Z_2B_2 + Z_3B_3 + \dots Z_nB_n, \quad (3.36)$$

where X = dimension or underlying component of factor,

Z_n = variables which comprise the factor,

B_n = relative weight of variable Z_n

A description of the parameters observed in the interpretation of principal factors analysis can be seen in Table 3.6.

Further analysis of the data in the current study consisted of correlation analysis. The correlation analysis tools used in this study included canonical correlation analysis and principal factors analysis. Canonical correlation analysis was performed on the data of the entire participant pool to detect any overall correlation between the fatigue analysis variables and the electromyography amplitude, kinematic, and kinetic variables.

Principal factors analysis was performed on the data of the entire participant pool to indicate the principal “factors” which accounted for the variance in the data and to detect any correlation among the fatigue analysis, electromyography amplitude, kinematic, and kinetic parameters.

Table 3.6 Summary of parameters observed in interpretation of PFA

Canonical Parameter	Description
Factor	Linear combination of a set of original variables, from which the canonical function is derived.
Kaiser Criterion	Statistical test criterion which ensures that a factor extracts at least as much variation as an original variable. Factors that extract less variation than an average standardized original variable are not retained.
Factorial Loading	Weights in the linear equation of variables that create the factor. Describes the correlation between the original variable and the corresponding factor.

Subsequent to these analyses, the data were divided into three (3) separate data sets, each corresponding to one of three lifting postures selected. Canonical correlation and principal factors analyses were performed on the data corresponding to each posture selected, to detect any further correlation of the variables as stratified by posture. The complete SAS v8.1 programs used to perform the canonical correlation and principal factors analyses of the data can be viewed in Appendices G and H, respectively.

CHAPTER 4

RESULTS

All results were analyzed using SAS v8.1 statistical software package. The results were first analyzed using multivariate analysis of variance (MANOVA) to determine the presence of any overall effect of the independent variables and their interactions. Where the existence of any significant overall effect was determined, considering the Wilk's lambda criterion at the $\alpha=0.05$ level, individual analyses of variance were performed for each dependent variable. Where any significant effect of the independent variables or their interaction was detected, least squares means tests utilizing the Tukey-Kramer adjustment for multiple comparisons were performed. Results were also analyzed utilizing canonical correlation and principal factors analysis to determine any existing interrelationships between dependent variables.

The results are presented in four sections dealing with 1.) overall MANOVA results, 2.) fatigue analysis parameters, 3.) electromyography amplitude, kinematic, and kinetic parameters, and 4.) correlation analysis of the parameters observed. Sections 2 and 3 generalize results across the entire subject pool. Results reported in sections 2 and 3 are presented, where any significant overall MANOVA results are observed, in the order of separate ANOVA followed by least squares means results for individual dependent variables. Section 4 first presents generalized results across the entire subject pool, then presents results according to each lifting posture selected. Results reported in section 4 are presented in the order of overall canonical correlation coefficients and principal factors analysis coefficients for all subjects followed by those for each posture assumed.

4.1 Multivariate Analysis of Variance

Multivariate analysis of variance was performed to determine any overall effects of time ($\beta_j, j=0,1,2,3,4,5,6,7,8$), lifting posture selected ($\gamma_k, k=1,2,3$), and their interaction on fatigue analysis, electromyography amplitude, kinematic, and kinetic parameters. Multiple analysis of variance test criteria and p-values are displayed in Table 5.1. The overall effect of posture was significant at $p<.0001$ level and the overall effect of time was significant at $p=.0341$ level. A significant overall effect of the posture*time interaction was not observed.

Table 4.1 Summary of multiple analysis of variance for all dependent variables (Significant p-values at $\alpha=.05$ level are displayed as bold.)

	Wilk's Lambda				
Variable	Value	F	Numerator DF	Denominator DF	Pr>F
Posture	0.00083422	44.24	38	50	<.0001
Time	0.00972387	1.34	133	175.69	0.0341
Posture*Time	0.00090033	1.03	266	320.86	0.3840

4.2 Fatigue Analysis Parameters

The fatigue analysis parameters which are presented in this section are normalized median frequencies of EMG of the thoracic erector spinae (TESFreq), the lumbar erector spinae (LESFreq), and of the vastii lateralis (VLFreq); subjective fatigue rating (fatigue); normalized static composite strength (sstrength); and normalized dynamic leg lift floor to knuckle height strength (dstrength). Figures 4.1-4.6 display the fatigue analysis parameter mean values $\pm$ one standard deviation, across all subjects observed across the

experimental trials. Average data across all subjects and individual subject data can be viewed in Appendix I.

Figure 4.1 displays the normalized median frequency values of the thoracic erector spinae (TES) muscles over the course of the experiment. The average normalized median frequency of the TES is greatest at 45 minutes and is at its lowest value at 60 minutes, whereas the standard deviation across subjects is least at 45 minutes and at its greatest value at the 105 minute point. Figure 4.2 displays the average normalized median frequency values of the lumbar erector spinae (LES) muscles. The average median frequency of the LES is greatest at 15 minutes and is lowest at 105 minutes. The standard deviation of the normalized LES median frequency values is least at 120 minutes and is greatest at 90 minutes. Figure 4.3 displays the average normalized median frequency values of the vastii lateralis (VL) muscles. The average normalized median frequency of the VL muscle groups is greatest at 120 minutes and is lowest at 30 minutes. The standard deviation of the normalized VL median frequency values is at its minimum point at 90 minutes and is at its greatest 75 minutes. Figure 4.4 displays the average subjective fatigue rating values of the subjects over the course of the experiment. The average subjective fatigue rating is lowest at 0 minutes and consistently increases to its maximum value at 120 minutes. The standard deviation of the subjective fatigue rating values is similarly at its minimum value at 0 minutes yet, it is at its greatest at 60 minutes. Figure 4.5 displays the average normalized static composite strength values at 0 minutes and 120 minutes. The average normalized static composite strength is greater at 0 minutes decreases by 20.7% at 120 minutes, with a standard deviation of 0.209. Figure 4.6 displays the average normalized dynamic leg lift floor to knuckle height strength.

The average normalized dynamic strength is least at 60 minutes and is at its greatest value at 120 minutes. The standard deviation of the normalized dynamic strength values is at its minimum point at 0 minutes, where the dynamic strength was normalized to 1. The standard deviation consistently increases over time to reach its maximum value at 120 minutes.

4.2.1 Analysis of Variance (ANOVA) Results

Independent analyses of variance (ANOVA) were performed to test for fixed effects of posture and time on each dependent variable as MONOVA results indicated significant overall effects of posture and time. ANOVA results for the independent variable effects on fatigue analysis parameters are given in Table 4.2.

Figure 4.1 Normalized Median Frequency of the Thoracic Erector Spinae vs. Time

Figure 4.2 Normalized Median Frequency of the Lumbar Erector Spinae vs. Time

Figure 4.3 Normalized Median Frequency of the Vastii Lateralis vs. Time

Figure 4.4 Subjective Fatigue Rating vs. Time

Figure 4.5 Normalized Static Composite Strength vs. Time

Figure 4.6 Normalized Dynamic Leglift Floor to Knuckle Height Strength vs. Time

Table 4.2 Summary of results of analysis of variance with fatigue analysis parameters as dependent variables (Significant p-values at $\alpha=.05$ level are displayed as bold. Marginally significant p-values [$.05<\alpha<1$] are displayed as italicized.)

		TESFreq	LESFreq	VLFreq	fatigue	sstrength	dstrength
Posture	F	0.03	1.85	0.73	1.14	1.27	3.17
	Pr>F	0.9678	0.2263	0.5171	0.3739	0.3392	0.1046
Time	F	0.78	0.65	2.19	17.78	10.28	1.47
	Pr>F	0.6047	0.7153	<i>0.0531</i>	<.0001	0.0184	0.1904
Posture*Time	F	0.39	1.22	0.91	0.46	1.27	2.10
	Pr>F	0.9703	0.2947	0.5542	0.9554	0.3476	0.0237

The results of this analysis are as follows:

1. Normalized Median Frequency of the Thoracic Erector Spinae (TESFreq)
 - TES frequency did not behave differently under different postures.
 - TES frequency did not behave differently across different times.
 - TES frequency did not behave differently under different postures across different times.

2. Normalized Median Frequency of the Lumbar Erector Spinae (LESFreq)
 - LES frequency did not behave differently under different postures.
 - LES frequency did not behave differently across different times.
 - LES frequency did not behave differently under different postures across different times.

3. Normalized Median Frequency of the Vastii Lateralis (VLFreq)
 - VL frequency did not behave differently under different postures.
 - VL frequency did trend towards behaving differently across different times at 0.0531 level.
 - VL frequency did not behave differently under different postures across different times.
4. Subjective Fatigue Rating (Fatigue)
 - Fatigue did not behave differently under different postures.
 - Fatigue did behave differently across different times at 0.0001 level.
 - Fatigue did not behave differently under different postures across different times.
5. Normalized Static Composite Strength (Sstrength)
 - Sstrength did not behave differently under different postures.
 - Sstrength did behave differently across different times at 0.0184 level.
 - Sstrength did not behave differently under different postures across different times.
6. Normalized Dynamic Leglift Floor to Knuckle Height Strength (Dstrength)
 - Dstrength did not behave differently under different postures.
 - Dstrength did not behave differently across different times.
 - Dstrength did behave differently under different postures across different times at 0.0237 level.

4.2.2 Least Squares Means Test Results

Least squares means tests utilizing the Tukey-Kramer adjustment for multiple comparisons were performed where any significant ($\alpha=0.05$) or marginally significant ($0.05<\alpha<1$) effect of posture, time, or the posture and time interaction was observed in order to determine significant differences in parameters across postures, times, or their interactions. Tables 4.3 – 4.7 show the difference of least squares means results for each analyzed independent variable.

Table 4.3 summarizes results of the least squares means tests for normalized lumbar erector spinae median frequency across time. The difference in the mean values of the normalized lumbar erector spinae median frequency at time 2 (30 minutes) and time 8 (120 minutes) was marginally significant at 0.0648 level. Table 4.4 summarizes results of the least squares means tests for subjective fatigue rating across time. Differences between mean fatigue rating at time 0 and times 2 (30 minutes), 3 (45 minutes), 4 (60 minutes), 5 (75 minutes), 6 (90 minutes), 7 (105 minutes), and 8 (120 minutes) were all significant at 0.0001 level, with the exception of that with time 2, which was significant at 0.0039 level. Differences between subjective fatigue rating at time 1 (15 minutes) and times 3, 4, 5, 6, 7, and 8 were significant at 0.0476, 0.0053, 0.0009, and 0.0001 levels, respectively. Differences were significant between mean fatigue rating at time 2 and times 6, 7, and 8 at 0.0145, 0.0014, and 0.0002 levels, respectively. Further, between time 3 and time 8, a significant difference in subjective fatigue rating mean was observed at 0.0247 level. Table 4.5 summarizes results of the least squares means tests for normalized static composite strength, indicating a significant difference between static strength at time 0 and at time 8 at 0.0184 level. Table 4.6

summarizes significant and marginally significant results of the least squares means tests for normalized dynamic leglift floor to knuckle height strength across postures over time. Within posture 1 (semi-squat), there were significant differences in dynamic strength between time 0 and times 7 and 8 at 0.0250 and 0.0024 levels respectively. There was a marginally significant difference (at 0.0606 level) between dynamic leglift floor to knuckle height strength in posture 1 at time 8 and posture 2 at time 6. Mean normalized dynamic leglift floor to knuckle height strength stratified by posture over time is displayed graphically in Figure 4.7.

Table 4.3 Summary of results of least squares means tests utilizing the Tukey-Kramer adjustment for multiple comparisons for normalized vastii lateralis median frequency across time (Significant p-values at $\alpha=.05$ level are displayed as bold. Marginally significant p-values [$.05 < \alpha < 1$] are displayed as italicized.)

time	time ¹	t Value	Pr > t	Adjusted p- value	time	time ¹	t Value	Pr > t	Adjusted p- value
1	2	2.58	0.0132	0.1900	3	5	0.26	0.7987	1.0000
1	3	1.30	0.1990	0.8925	3	6	-0.18	0.8559	1.0000
1	4	1.58	0.1207	0.7578	3	7	-1.41	0.1653	0.8473
1	5	1.53	0.1332	0.7873	3	8	-1.88	0.0667	0.5713
1	6	1.09	0.2814	0.9555	4	5	-0.02	0.9878	1.0000
1	7	-0.14	0.8911	1.0000	4	6	-0.45	0.6516	0.9998
1	8	-0.66	0.5117	0.9976	4	7	-1.68	0.0995	0.6978
2	3	-1.28	0.2079	0.9020	4	8	-2.14	0.0379	0.4065
2	4	-1.00	0.3230	0.9721	5	6	-0.43	0.6688	0.9999
2	5	-0.99	0.3269	0.9733	5	7	-1.64	0.1092	0.7269
2	6	-1.43	0.1596	0.8381	5	8	-2.09	0.0427	0.4384
2	7	-2.66	0.0109	0.1630	6	7	-1.20	0.2349	0.9263
2	8	-3.07	0.0036	0.0648	6	8	-1.67	0.1011	0.7028
3	4	0.28	0.7819	1.0000	7	8	-0.52	0.6054	0.9995

Table 4.4 Summary of results of least squares means tests utilizing the Tukey-Kramer adjustment for multiple comparisons for subjective fatigue rating across time (Significant p-values at $\alpha=.05$ level are displayed as bold.)

time	time ¹	t Value	Pr > t	Adjusted p-value	time	time ¹	t Value	Pr > t	Adjusted p-value
0	1	-2.43	0.0186	0.2906	2	6	-3.69	0.0005	0.0145
0	2	-4.13	0.0001	0.0039	2	7	-4.45	<.0001	0.0014
0	3	-5.68	<.0001	<.0001	2	8	-5.02	<.0001	0.0002
0	4	-6.46	<.0001	<.0001	3	4	-0.78	0.4405	0.997
0	5	-6.96	<.0001	<.0001	3	5	-1.42	0.162	0.8855
0	6	-7.71	<.0001	<.0001	3	6	-2.18	0.0341	0.436
0	7	-8.47	<.0001	<.0001	3	7	-2.93	0.005	0.1042
0	8	-9.04	<.0001	<.0001	3	8	-3.5	0.001	0.0247
1	2	-1.7	0.095	0.7434	4	5	-0.66	0.5113	0.9991
1	3	-3.26	0.002	0.0476	4	6	-1.42	0.162	0.8855
1	4	-4.03	0.0002	0.0053	4	7	-2.18	0.0341	0.436
1	5	-4.59	<.0001	0.0009	4	8	-2.74	0.0083	0.1581
1	6	-5.35	<.0001	<.0001	5	6	-0.74	0.4601	0.9978
1	7	-6.1	<.0001	<.0001	5	7	-1.49	0.1427	0.8557
1	8	-6.67	<.0001	<.0001	5	8	-2.05	0.0458	0.5194
2	3	-1.55	0.1261	0.824	6	7	-0.74	0.4601	0.9978
2	4	-2.33	0.0236	0.3427	6	8	-1.3	0.1985	0.9261
2	5	-2.93	0.005	0.1042	7	8	-0.56	0.5791	0.9997

Table 4.5 Summary of results of least squares means test for static composite strength across time (Significant p-values at $\alpha=.05$ level are displayed as bold.)

time	time ¹	t Value	Pr > t
0	8	3.21	0.0184

Table 4.6 Summary of significant results of least squares means tests utilizing the Tukey-Kramer adjustment for multiple comparisons for dynamic leglift floor to knuckle height strength across postures over time (Significant p-values at $\alpha=.05$ level are displayed as bold. Marginally significant p-values $[.05 < \alpha < 1]$ are displayed as italicized.)

Posture	Time	Posture ¹	Time ¹	t Value	Pr > t	Adjusted p-value
1	0	1	7	-4.16	0.0001	0.0250
1	0	1	8	-4.94	<.0001	0.0024
1	8	2	6	3.84	0.0003	<i>0.0606</i>

Figure 4.7 Normalized Dynamic Leglift Floor to Knuckle Height Strength by Posture vs. Time

4.3 Electromyography Amplitude, Kinematic, And Kinetic Parameters

The electromyography (EMG) amplitude, kinematic, and kinetic parameters which are presented in this section are normalized amplitude of EMG of thoracic erector spinae (TESMAV), normalized amplitude of EMG of lumbar erector spinae (LESMAV), normalized amplitude of EMG vastii lateralis (VLMAV), duration of the lift (Duration), peak vertical load acceleration (PeakVertAcc), average force on hands (HandForce), peak trunk flexion angle (PeakFlex), peak trunk extension velocity (PeakExtVel), peak shear force at L5/S1 joint (PeakShear), peak compression force at L5/S1 joint (PeakCom), peak moment at L5/S1 joint (PeakMom), Integrated moment at L5/S1 joint (Imoment), trunk flexion angle at initiation of lift (Flx), and knee angle at initiation of lift (Knee). Figures 4.8-4.21 display the EMG amplitude, kinematic, and kinetic parameter values observed across the experimental trials averaged across all subjects. Average data across all subjects and individual subject data can be viewed in Appendix I.

Figure 4.8 displays the average normalized thoracic erector spinae (TES) EMG mean absolute value over the course of the experiment. The average normalized median mean absolute value of the TES is greatest at 30 minutes and is at its lowest value at 120 minutes, whereas the standard deviation across subjects is least at 120 minutes and at its greatest value at the 60 minute point. Figure 4.9 displays the average normalized EMG mean absolute value of the lumbar erector spinae (LES) muscles. The mean absolute value of the LES is greatest at 120 minutes and is lowest at 15 minutes. The standard deviation of the normalized LES EMG mean absolute value is least at 120 minutes and is greatest at 90 minutes. Figure 4.10 displays the average normalized EMG mean absolute value of the vastii lateralis (VL) muscles. The average normalized mean absolute value

of the VL muscle groups is greatest at 30 minutes and is lowest at 75 minutes. The standard deviation of the normalized VL EMG mean absolute value is at its minimum point at 90 minutes and is at its greatest 15 minutes.

Figure 4.11 displays the average duration of the lift cycle over the course of the experiment. The average lift cycle period is greatest at 15 minutes and is shortest at 75 minutes. The standard deviation of lift cycle duration across subjects is least at 120 minutes and at its greatest value at the 30 minute point. Figure 4.12 displays the average peak vertical acceleration of the load over time. The average peak vertical acceleration is greatest at 45 minutes and is least at 105 minutes. The standard deviation of the peak vertical acceleration is at its greatest at 15 minutes and at its lowest at 120 minutes. Figure 4.13 displays the average force on the hands during the lift cycle over the course of the experiment. The average force on the hands was greatest at 60 minutes and was lowest at 120 minutes. Likewise, the standard deviation of the average hand force across subjects was greatest at 60 minutes and lowest at 120 minutes. Figure 4.14 displays the average peak forward flexion angle of L5/S1 joint during the lift cycle, indicating the greatest average flexion angle at 45 minutes and the smallest average angle of lumbosacral flexion at 30 minutes. Conversely, the standard deviation of the peak forward flexion angle of L5/S1 joint across subjects was greatest at 30 minutes and lowest at 45 minutes. Figure 4.15 displays the average peak angular extension velocity of L5/S1 joint. The peak extension velocity was least at the 15 minute point and was greatest at 120 minutes. The standard deviation of the peak angular extension velocity across subjects was greatest at 30 minutes and was lowest at 120 minutes.

Figure 4.16 displays the average peak shear force acting on the L5/S1 joint over time during the experiment. The average peak shear force is greatest at 45 minutes and is least at 105 minutes. The standard deviation of the peak lumbosacral shear force is similarly greatest at 45 minutes and is lowest at 120 minutes. Figure 4.17 displays the average peak compressive force acting on the L5/S1 joint over time. The average peak compressive force was least at 75 minutes and was greatest at 120 minutes. The standard deviation of the peak compressive force across subjects was least at 30 minutes and was at its greatest at 60 minutes. The average peak inertial moment acting on the L5/S1 joint over time is displayed in Figure 4.18. The average peak moment is lowest at 75 minutes and is greatest at 120 minutes. The standard deviation of the average peak moment across subjects is greatest at 60 minutes and is least at 90 minutes. Figure 4.19 displays the average inertial moment acting on the L5/S1 joint in the counter-clockwise direction, integrated over the duration of the lift cycle. The integrated moment was greatest at 75 minutes and at its lowest at 30 minutes, while the standard deviation of the integrated moment was greatest at 30 minutes and lowest at 60 minutes.

The average forward flexion angle of L5/S1 joint at the initiation of the lift cycle over time is displayed in Figure 4.20. The average initial flexion angle is smallest at 30 minutes and is greatest at 105 minutes. The standard deviation of the initial flexion angle is greatest at 60 minutes and lowest at 75 minutes. Figure 4.21 displays the average included angle of the knee joint at the initiation of the lift cycle. Similarly to the initial flexion angle, the initial knee angle is smallest at 30 minutes and is greatest at 105 minutes. The standard deviation of the initial knee angle across subjects is at its lowest at 45 minutes and at its greatest at 90 minutes.

Figure 4.8 Normalized Thoracic Erector Spinae Mean Absolute Value vs. Time

Figure 4.9 Normalized Lumbar Erector Spinae Mean Absolute Value vs. Time

Figure 4.10 Normalized Vastii Lateralis Mean Absolute Value vs. Time

Figure 4.11 Duration of Lift Cycle vs. Time

Figure 4.12 Peak Vertical Acceleration of the Load vs. Time

Figure 4.13 Average Force on the Hands During the Lift vs. Time

Figure 4.14 Peak Forward Flexion Angle of L5/S1 Joint vs. Time

Figure 4.15 Peak Angular Extension Velocity of L5/S1 Joint vs. Time

Figure 4.16 Peak Shear Force Acting on L5/S1 Joint vs. Time

Figure 4.17 Peak Compression Force Acting on L5/S1 Joint vs. Time

Figure 4.18 Peak Inertial Moment Acting on L5/S1 Joint vs. Time

Figure 4.19 Integrated Inertial Moment Acting on L5/S1 Joint Over a Single Lift (+ in counterclockwise direction) vs. Time

Figure 4.20 Forward Flexion Angle of L5/S1 Joint at Initiation of Lift vs. Time

Figure 4.21 Included Angle of Knee Joint at Initiation of Lift vs. Time

4.3.1 Analysis of Variance (ANOVA) Results

Independent analyses of variance (ANOVA) were performed to test for fixed effects of posture and time on each dependent variable as MONOVA results indicated significant overall effects of posture and time. ANOVA results for the independent variable effects on electromyography (EMG) amplitude, kinematic, and kinetic parameters are given in Table 4.7.

The results of this analysis are as follows:

1. Normalized EMG Mean Absolute Value of the Thoracic Erector Spinae (TESMAV)
 - TESMAV did not behave differently under different postures.
 - TESMAV did not behave differently across different times.
 - TESMAV did not behave differently under different postures across different times.

2. Normalized EMG Mean Absolute Value of the Lumbar Erector Spinae (LESMAV)
 - LESMAV did trend toward behaving differently under different postures at 0.0505 level.
 - LESMAV did trend toward behaving differently across different times at 0.0658 level.
 - LESMAV did not behave differently under different postures across different times.

3. Normalized EMG Mean Absolute Value of the Vastii Lateralis (VLMAV)
 - VLMAV did not behave differently under different postures.
 - VLMAV did not behave differently across different times.
 - VLMAV did not behave differently under different postures across different times.
4. Duration of Lift Cycle (Duration)
 - Duration did not behave differently under different postures.
 - Duration did not behave differently across different times.
 - Duration did not behave differently under different postures across different times.
5. Peak Vertical Acceleration of Load (PeakVertAcc)
 - PeakVertAcc did not behave differently under different postures.
 - PeakVertAcc did not behave differently across different times.
 - PeakVertAcc did not behave differently under different postures across different times.
6. Average Force on Hands During Lift Cycle (HandForce)
 - HandForce did not behave differently under different postures.
 - HandForce did not behave differently across different times.
 - HandForce did not behave differently under different postures across different times.

7. Peak Forward Flexion Angle of L5/S1 Joint (PeakFlex)
 - PeakFlex did behave differently under different postures at 0.0122 level.
 - PeakFlex did not behave differently across different times.
 - PeakFlex did not behave differently under different postures across different times.
8. Peak Angular Extension Velocity of L5/S1 Joint (PeakExtVel)
 - PeakExtVel did not behave differently under different postures.
 - PeakExtVel did not behave differently across different times.
 - PeakExtVel did not behave differently under different postures across different times.
9. Peak Shear Force Acting on L5/S1 Joint (PeakShear)
 - PeakShear did not behave differently under different postures.
 - PeakShear did not behave differently across different times.
 - PeakShear did not behave differently under different postures across different times.
10. Peak Compression Force Acting on L5/S1 Joint (PeakCom)
 - PeakCom did not behave differently under different postures.
 - PeakCom did not behave differently across different times.
 - PeakCom did not behave differently under different postures across different times.

11. Peak Inertial Moment Acting on L5/S1 Joint (PeakMom)
 - PeakMom did not behave differently under different postures.
 - PeakMom did not behave differently across different times.
 - PeakMom did not behave differently under different postures across different times.
12. Inertial Moment Acting on L5/S1 Joint Integrated Over One Lift (IMoment)
 - IMoment did not behave differently under different postures.
 - IMoment did not behave differently across different times.
 - IMoment did not behave differently under different postures across different times.
13. Forward Flexion Angle of L5/S1 Joint at Initiation of Lift (Flx)
 - Flx did behave differently under different postures at 0.0090 level.
 - Flx did not behave differently across different times.
 - Flx did not behave differently under different postures across different times.
14. Included Knee Angle Joint at Initiation of Lift (Knee)
 - Knee did behave differently under different postures at 0.0007 level.
 - Knee did not behave differently across different times.
 - Knee did not behave differently under different postures across different times.

Table 4.7 Summary of results of analysis of variance with electromyography amplitude, kinematic, and kinetic parameters as dependent variables (Significant p-values at $\alpha=.05$ level are displayed as bold.)

		TES MAV	LES MAV	VL MAV	Duration	PeakVert Acc	Hand Force	PeakFlex
Posture	F	0.47	4.71	1.86	0.09	0.02	0.22	8.82
	Pr>F	0.641	0.0505	0.2255	0.9108	0.9837	0.8104	0.0122
Time	F	0.61	2.08	0.24	0.29	1.09	1.53	1.03
	Pr>F	0.7441	0.0658	0.9729	0.9542	0.3884	0.1813	0.4214
Posture* Time	F	1.5	1.15	1.1	0.69	0.57	0.76	0.76
	Pr>F	0.1509	0.344	0.3834	0.7726	0.8751	0.7026	0.7014
		Peak ExtVel	Peak Shear	PeakCom	Peak Mom	IMoment	Flx	Knee
Posture	F	1.69	0.51	0.69	0.99	0.21	9.94	24.88
	Pr>F	0.2527	0.6207	0.5325	0.417	0.8132	0.009	0.0007
Time	F	1.01	0.6	1.47	1.23	0.88	1.11	1.15
	Pr>F	0.4365	0.7489	0.2034	0.3064	0.5268	0.375	0.3514
Posture* Time	F	1.57	1.32	1.37	1.65	0.98	0.65	1.45
	Pr>F	0.1258	0.2363	0.2102	0.1037	0.4843	0.8056	0.1705

4.3.2 Least Squares Means Test Results

Least squares means tests utilizing the Tukey-Kramer adjustment for multiple comparisons were performed where any significant ($\alpha=0.05$) or marginally significant

($\alpha < 1$) effect of posture, time, or the posture and time interaction was observed in order to determine significant differences in parameters across postures, times, or their interactions. Tables 4.8 – 4.12 show the difference of least squares means results for each analyzed independent variable.

Table 4.8 summarizes results of the least squares means tests for normalized EMG mean absolute value of the lumbar erector spinae across postures, indicating a significant difference between EMG mean absolute value in posture 1 (semi-squat) and in posture 3 (stoop) at 0.0446 level. Table 4.9 summarizes results of the least squares means tests for normalized EMG mean absolute value of the lumbar erector spinae across time. A marginally significant difference (at 0.0559 level) was observed in mean absolute value of the lumbar erector spinae EMG between time 1 and time 8. Table 4.10 summarizes results of the least squares means tests for peak forward flexion angle at L5/S1 joint across postures, indicating a significant difference in peak flexion angle between posture 1 (semi-squat) and in posture 3 (stoop) at 0.0099 level. Table 4.11 summarizes results of the least squares means tests for forward flexion angle at L5/S1 joint at the initiation of the lift across postures, indicating a significant differences in flexion angle between posture 1 (semi-squat) and in postures 2 (semi-stoop) and 3 (stoop) at 0.0834 and 0.0073 levels, respectively. Table 4.12 summarizes results of the least squares means tests for knee joint angle at the initiation of the lift across postures. Significant differences were observed in initial knee angle between posture 1 and postures 2 and 3 at 0.0210 and 0.0005 levels, respectively, and between postures 2 and three at 0.0140 level.

Table 4.8 Summary of significant results of least squares means tests utilizing the Tukey-Kramer adjustment for multiple comparisons for normalized EMG mean absolute value of the lumbar erector spinae across postures (Significant p-values at $\alpha=.05$ level are displayed as bold.)

posture	posture ¹	t Value	Pr > t	Adjusted p-value
1	2	2.02	0.0836	0.1785
1	3	3.03	0.0191	0.0446
2	3	1.18	0.2764	0.5003

Table 4.9 Summary of significant results of least squares means tests utilizing the Tukey-Kramer adjustment for multiple comparisons for normalized EMG mean absolute value of the lumbar erector spinae across time (Marginally significant p-values [$.05 < \alpha < 1$] are displayed as italicized.)

time	time ¹	t Value	Pr > t	Adjusted p-value	time	time ¹	t Value	Pr > t	Adjusted p-value
1	2	-0.36	0.7222	1	3	5	-0.68	0.4992	0.9971
1	3	-1.1	0.2777	0.9536	3	6	-0.61	0.5482	0.9986
1	4	-1.82	0.0751	0.6083	3	7	-1.26	0.2131	0.9072
1	5	-1.75	0.0865	0.6535	3	8	-2.11	0.0405	0.4239
1	6	-1.68	0.1006	0.7014	4	5	0.02	0.9804	1
1	7	-2.34	0.0242	0.2984	4	6	0.1	0.9201	1
1	8	-3.14	0.0031	0.0559	4	7	-0.56	0.5801	0.9992
2	3	-0.74	0.4624	0.9951	4	8	-1.44	0.1579	0.8353
2	4	-1.47	0.1499	0.821	5	6	0.07	0.9407	1
2	5	-1.4	0.1673	0.8504	5	7	-0.57	0.5706	0.9991
2	6	-1.33	0.191	0.8831	5	8	-1.44	0.1581	0.8356
2	7	-1.99	0.0532	0.5022	6	7	-0.65	0.5214	0.9979
2	8	-2.8	0.0075	0.1206	6	8	-1.51	0.1388	0.7993
3	4	-0.72	0.4729	0.9958	7	8	-0.89	0.3789	0.9856

Table 4.10 Summary of significant results of least squares means tests utilizing the Tukey-Kramer adjustment for multiple comparisons for peak forward flexion angle at L5/S1 joint across postures (Significant p-values at $\alpha=.05$ level are displayed as bold.)

posture	posture ¹	t Value	Pr > t	Adjusted p-value
1	2	-2.42	0.0463	0.1033
1	3	-4.19	0.0041	0.0099
2	3	-2.06	0.0786	0.1686

Table 4.11 Summary of significant results of least squares means tests utilizing the Tukey-Kramer adjustment for multiple comparisons for forward flexion angle at L5/S1 joint at the initiation of the lift across postures (Significant p-values at $\alpha=.05$ level are displayed as bold. Marginally significant p-values [$.05 < \alpha < 1$] are displayed as italicized.)

posture	posture ¹	t Value	Pr > t	Adjusted p-value
1	2	-2.57	0.0369	<i>0.0834</i>
1	3	-4.45	0.0030	0.0073
2	3	-2.18	0.0659	0.1435

Table 4.12 Summary of significant results of least squares means tests utilizing the Tukey-Kramer adjustment for multiple comparisons for included knee joint angle at the initiation of the lift across postures (Significant p-values at $\alpha=.05$ level are displayed as bold.)

posture	posture ¹	t Value	Pr > t	Adjusted p-value
1	2	-3.60	0.0088	0.0210
1	3	-7.05	0.0002	0.0005
2	3	-3.91	0.0058	0.0140

4.4 Correlation Analysis

The results of the correlation analysis are presented in this section. These results include canonical correlation analysis (CCA), which indicates underlying structure and correlations between the fatigue analysis variables and the electromyography amplitude, kinematic, and kinetic variables. Further, the results include principal factors analysis (PFA), which indicates underlying structure and correlations among the fatigue analysis, electromyography amplitude, kinematic, and kinetic variables. Results are presented first as generalized results across the entire subject pool. The results are subsequently presented independently for each of the lifting techniques (semi-squat, semi-stoop, and stoop) observed.

4.4.1 Canonical Correlation Analysis Results of Entire Subject Pool

Canonical correlation analysis was performed on the data of the entire subject pool to detect any correlation between the fatigue analysis variables (normalized median frequency of EMG of the thoracic erector spinae, normalized median frequency of EMG the of the lumbar erector spinae, normalized median frequency of EMG of the vastii

lateralis, subjective fatigue rating, normalized static composite strength, and normalized dynamic leg lift floor to knuckle height strength) and the electromyography amplitude (normalized amplitude of EMG of the thoracic erector spinae, lumbar erector spinae, and vastii lateralis), kinematic (duration of the lift cycle, peak vertical load acceleration, peak trunk flexion angle, peak trunk extension velocity, and trunk flexion and knee angles at initiation of lift), and kinetic (average force on the hands; peak shear force, peak compression force, peak moment, and the integrated moment over the duration of the lift at L5/S1 joint) variables. Canonical correlation test statistics, standardized variance explained by the model, and canonical loading and cross loading results are given in Tables 4.13, 4.14, 4.15, and 4.16-4.17, respectively.

Table 4.13 shows that canonical correlation analysis indicates, at $\alpha=0.05$ level, three (3) significant canonical variates that account for a significant proportion of variation in the data for both fatigue analysis parameters and for EMG amplitude, kinematic, and kinetic parameters. For simplicity in reporting, in the current analysis, fatigue analysis parameters are referred to as “VAR variables” and the EMG amplitude, kinematic, and kinetic parameters are referred to as “WITH variables.” Significant canonical variates detected are labeled 1-3, in descending order of Cumulative R-Square value between VAR and WITH canonical variates. The cumulative R-Square value indicates the portion of variation in the WITH canonical variate explained or predicted by the corresponding VAR canonical variate. The cumulative R-Square values for canonical variates 1-3 displayed in Table 4.13 were 0.6526, 0.4687, and 0.3694 respectively.

4.4.1.1 VAR (Fatigue Analysis) Variables and the Canonical Variates

Table 4.14 indicates that canonical VAR variates 1-3 explain a total of 57.17% of the variation present in the original VAR variables and that WITH variates 1-3 share in commonly explaining 28.44% of that total variation. 17.58% of the variation in the original VAR variables is explained by canonical VAR variate 1. Table 4.15 shows that this canonical VAR variate 1 is highly loaded on the VAR variable subjective fatigue rating (0.8881) and possesses weak loadings on vastii lateralis normalized EMG frequency (0.3284) and on dynamic leglift floor to knuckle height strength (-0.3714). Canonical WITH variate 1, which accounts for 11.47% of the variation in the original VAR variables, is highly cross loaded on the VAR variable subjective fatigue rating (0.7174), as can be observed in Table 4.16. Canonical VAR variate 2, which accounts for 23.58% of the variation present in the original VAR variables, was observed to load highly on the VAR variables dynamic leglift floor to knuckle height strength (0.8023) and lumbar erector spinae normalized EMG frequency (0.7066) and moderately on the VAR variable vastii lateralis normalized EMG frequency (0.4531). Similarly, canonical WITH variate 2, which explains 11.05% of the variation in the original VAR variables, possessed moderate loading factors on the VAR variables dynamic leglift floor to knuckle height strength (0.5492) and lumbar erector spinae normalized EMG frequency (0.4837) and a weak loading on the VAR variable vastii lateralis normalized EMG frequency (0.3102). Accounting for 16.01% of the variation in the original VAR variables, canonical VAR variate 3 was seen to load extremely highly and solely on VAR variable thoracic erector spinae normalized EMG frequency (-0.9155). Likewise, canonical WITH variate 3, which explains 5.91% of the variation in the VAR variables

loaded solely, but moderately on VAR variable thoracic erector spinae normalized EMG frequency (-0.5564).

4.4.1.2 WITH (EMG Amplitude, Kinematic, and Kinetic) variables and the Canonical Variates

Canonical WITH variates 1-3 explain a total of 33.8% of the variation present in the original WITH variables and canonical VAR variates 1-3 share in commonly explaining 16.74% of that total variation. 8.73% of the variation in the original WITH variables is explained by canonical WITH variate 1, which is observed to load moderately on WITH variables peak moment (0.4642), peak compressive force (0.4509), and peak shear force (0.4055) at L5/S1 joint and to load weakly on average hand force (0.3677), peak lumbosacral flexion angle (0.3665), and lumbosacral flexion angle at initiation of lift (0.3387). Canonical VAR variate 1 accounts for 5.7% of the variation in the original WITH variables and is seen to load weakly on WITH variables peak moment (0.375), peak compressive force (0.3643), and peak shear force (0.3276) at L5/S1 joint. Canonical WITH variate 2 accounted for 17.91% of the total variation of the original WITH variables and loaded highly on the WITH variables lumbar erector spinae normalized EMG amplitude (0.6736) and knee angle at initiation of lift (-0.6426), and moderately on WITH variables duration of lift cycle (-0.5549), thoracic erector spinae normalized EMG amplitude (0.5505), peak vertical acceleration of the load (-0.4635), average force on hands (-0.4545), peak lumbosacral shear force (-0.4431), lumbosacral flexion angle at initiation of lift (-0.4283) and peak lumbosacral flexion (-0.4025). Canonical VAR variate 2, which accounts for 8.4% of the total variation in the original WITH variables was observed to load moderately on WITH variables lumbar erector

spinae normalized EMG amplitude (0.4611) and knee angle at initiation of lift (-0.4399), and weakly on WITH variables duration of lift cycle (-0.3799), thoracic erector spinae normalized EMG amplitude (0.346), and peak vertical acceleration of the load (-0.3173). An additional 7.15% of the total variation in the original WITH variables was explained in canonical WITH variate 3, which was observed to load moderately on WITH variables peak vertical acceleration of the load (0.5055) and duration of lift cycle (0.4208), and load weakly on WITH variables peak lumbosacral flexion (-0.3909) and average force on the hands (0.3412). Canonical VAR variate 3, which accounted for 2.64% of the variation in the original WITH variables did not load significantly on any of the original WITH variables.

Table 4.13 Summary of canonical correlation test statistics for entire subject pool (Significant p-values at $\alpha=.05$ level are displayed as bold.)

Test of H_0 : The Canonical Correlation in the current row and all that follow are zero				
Likelihood Ratio	F Value	Numerator DF	Denominator DF	Pr>F
0.06182599	2.37	84	307.36	<.0001
0.17799323	1.79	65	263.86	0.0008
0.33498379	1.49	48	217.76	0.0297
0.53123758	1.22	33	168.64	0.2046
0.73626405	0.96	20	116	0.5155
0.88837222	0.82	9	59	0.5968

Table 4.14 Summary of standardized variance of the original variables explained by the canonical variates for entire subject pool.

Standardized Variance of the VAR Variables Explained by					
	Their own canonical variates			The opposite canonical variates	
Canonical Variate Number	Proportion	Cumulative Proportion	Cumulative R-Square	Proportion	Cumulative Proportion
1	0.1758	0.1758	0.6526	0.1147	0.1147
2	0.2358	0.4116	0.4687	0.1105	0.2252
3	0.1601	0.5717	0.3694	0.0591	0.2844
4	0.2025	0.7742	0.2785	0.0564	0.3408
5	0.1033	0.8775	0.1712	0.0177	0.3585
6	0.1225	1	0.1116	0.0137	0.3721
Standardized Variance of the WITH Variables Explained by					
	Their own canonical variates			The opposite canonical variates	
Canonical Variate Number	Proportion	Cumulative Proportion	Cumulative R-Square	Proportion	Cumulative Proportion
1	0.0873	0.0873	0.6526	0.057	0.057
2	0.1791	0.2665	0.4687	0.084	0.141
3	0.0715	0.338	0.3694	0.0264	0.1674
4	0.0593	0.3973	0.2785	0.0165	0.1839
5	0.0985	0.4958	0.1712	0.0169	0.2008
6	0.0377	0.5335	0.1116	0.0042	0.205

Table 4.15 Summary of canonical loadings between investigated variables and their canonical variates for entire subject pool (Strong loadings are displayed as bold. Moderate to weak loadings are displayed as italicized.)

Correlations Between the VAR Variables and Their Canonical Variates			
	V1	V2	V3
Time	0.0536	0.1128	0.1648
TESFreq	0.1071	0.2213	-0.9155
LESFreq	-0.0759	0.7066	-0.2115
VLFreq	0.3284	0.4531	0.0431
Dstrength	-0.3714	0.8023	0.1768
Fatigue	0.8881	-0.0708	-0.1321
Correlations Between the WITH Variables and Their Canonical Variates			
	W1	W2	W3
TESMAV	-0.0289	0.5055	0.26
LESMAS	-0.0636	0.6736	-0.0107
VLMAV	0.1546	0.2474	-0.1523
Duration	-0.2326	-0.5549	0.4208
PeakVertAcc	-0.2736	-0.4635	0.5055
HandForce	0.3677	-0.4545	0.3412
PeakFlex	0.3665	-0.4025	-0.3909
PeakExtVel	0.2423	-0.0919	-0.0251
PeakShear	0.4055	-0.4431	0.2651
PeakCom	0.4509	0.0972	0.0524
PeakMom	0.4642	0.1866	-0.0083
Imoment	0.1836	-0.0275	0.153
Flx	0.3387	-0.4283	-0.2719
Knee	0.071	-0.6426	-0.1923

Table 4.16 Summary of canonical cross loadings between fatigue analysis variables and the electromyography amplitude, kinematic, and kinetic variates for entire subject pool (Strong loadings are displayed as bold. Moderate to weak loadings are displayed as italicized.)

Correlations Between the VAR Variables and the Canonical Variates of the WITH Variables			
	W1	W2	W3
Time	0.0433	0.0772	0.1002
TESFreq	0.0865	0.1515	-0.5564
LESFreq	-0.0613	0.4837	-0.1285
VLFreq	0.2653	0.3102	0.0262
Dstrength	-0.3001	0.5492	0.1075
Fatigue	0.7174	-0.0485	-0.0803

Table 4.17 Summary of canonical cross loadings between electromyography amplitude, kinematic, and kinetic variables and the fatigue analysis variates for entire subject pool (Moderate to weak loadings are displayed as italicized.)

Correlations Between the WITH Variables and the Canonical Variates of the VAR Variables			
	V1	V2	V3
TESMAV	-0.0234	<i>0.346</i>	0.158
LESMaV	-0.0514	<i>0.4611</i>	-0.0065
VLMAV	0.1249	0.1694	-0.0926
Duration	-0.1879	<i>-0.3799</i>	0.2558
PeakVertAcc	-0.221	<i>-0.3173</i>	0.3072
HandForce	0.2971	-0.3111	0.2074
PeakFlex	0.2961	-0.2755	-0.2376
PeakExtVel	0.1957	-0.0629	-0.0153
PeakShear	<i>0.3276</i>	-0.3033	0.1611
PeakCom	<i>0.3643</i>	0.0665	0.0319
PeakMom	<i>0.375</i>	0.1278	-0.0051
Imoment	0.1483	-0.0188	0.093
Flx	0.2736	-0.2932	-0.1653
Knee	0.0574	<i>-0.4399</i>	-0.1169

4.4.2 Principal Factors Analysis Results of Entire Subject Pool

Principal factors analysis was performed on the data of the entire subject pool to indicate the principal “factors” which accounted for the variance in the data and to detect any correlation among the fatigue analysis, electromyography amplitude, kinematic, and kinetic parameters. Utilizing the Kaiser criterion, principal factors analysis detected six (6) factors, which retained eigenvalues greater than 1 and accounted for the majority of the variation in the data. Factors detected are indicated as Factors 1-6 and are presented in the order of greatest to least amount of variance accounted for. Standardized variance explained by each factor and principal factors correlation coefficient results are given in Tables 4.16 and 4.17, respectively.

The results are as follows:

- Factor 1 accounted for the greatest amount of variance in the original data, yielding an eigenvalue of 3.512207. Factor 1 possessed extremely high loadings on original “postural” variables lumbosacral flexion at initiation of lift (0.93755), peak lumbosacral flexion (0.91642), and knee angle at initiation of lift (0.8712); moderate loadings on variables lumbar erector spinae normalized EMG amplitude (-0.5405) and frequency (-0.46787); and weak loadings on variables subjective fatigue rating (-0.39946) and vastii lateralis normalized EMG amplitude (0.34232).
- Factor 2 yielded an eigenvalue of 3.296952, accounting for a considerable amount of the variance in the original data. Factor 2 loaded highly on variables average force on hands (0.90868), peak lumbosacral shear force (0.86102), and thoracic

- erector spinae normalized frequency (-0.71952); moderately on variables peak vertical acceleration of the load (0.56404), lumbar erector spinae normalized EMG amplitude (-0.4747), duration of lift cycle (0.4508) and lumbar erector spinae normalized EMG frequency (-0.40317); and weakly on variable vastii lateralis normalized EMG amplitude (0.33146).
- With an eigenvalue of 2.404948, Factor 3 loaded extremely highly on original variables peak lumbosacral moment (0.95624) and compressive force (0.9463). Weak loading was observed in Factor 3 on variables vastii lateralis normalized EMG amplitude (0.37407) and frequency (0.32108), and peak lumbosacral/trunk extension velocity (0.31791).
 - An eigenvalue of 2.167678 was associated with Factor 4. High factorial loadings were observed for Factor 4 on variables dynamic leglift floor to knuckle height strength (-0.77359), duration of lift cycle (0.67037), and peak vertical acceleration of the load (0.66079). Low factorial loadings were seen for Factor 4 on variables vastii lateralis normalized EMG frequency (-0.34892) and amplitude (-0.34739).
 - Factor 5 yielded an eigenvalue of 1.785119 and loaded highly on the original variable time (0.81429). Moderate loadings were observed on variables vastii lateralis (0.57465) and thoracic erector spinae (0.53715) normalized EMG amplitude, and lumbar erector spinae normalized EMG frequency (0.50007).
 - Factor 6 returned an eigenvalue of 1.300829 and loaded highly on variables integrated lumbosacral moment (0.77155) and peak lumbosacral/trunk extension velocity (-0.64713).

4.4.3 Canonical Correlation Analysis Results According to Lifting Posture

The original data of the subject pool was divided into three (3) groups according to the lifting posture selected by participants. The three lifting postures observed were 1.) semi-squat, 2.) semi-stoop, and 3.) stoop postures. Once the data was divided, separate canonical correlation analyses were performed on the data for each posture selected to detect any correlation between the fatigue analysis variables and the EMG amplitude, kinematic, and kinetic variables during freestyle lifting under each posture. Canonical correlation test statistics, standardized variance explained by each model, and canonical loading and cross loading results are given in this order for semi-squat, semi-stoop, then stoop postures in Tables 4.20 through 4.34. For simplicity in reporting, fatigue analysis parameters are referred to as “VAR variables” and the EMG amplitude, kinematic, and kinetic parameters are referred to as “WITH variables.”

Table 4.18 Summary of eigenvalues for principal factors analysis factors detected for entire subject pool.

Variance Explained by Each Factor					
Factor1	Factor2	Factor3	Factor4	Factor5	Factor6
3.512207	3.296952	2.404948	2.167678	1.785119	1.300829

Table 4.19 Summary of principal factors analysis factorial loadings between original variables and corresponding factors for entire subject pool (Strong loadings are displayed as bold. Moderate to weak loadings are displayed as italicized.)

Rotated Factor Pattern						
	Factor1	Factor2	Factor3	Factor4	Factor5	Factor6
Time	0.07935	-0.15691	0.0049	0.13141	0.81429	0.11234
TESFreq	-0.03852	-0.71952	0.20732	0.13274	0.25802	0.10615
LESFreq	-0.46787	-0.40317	0.04168	-0.1803	0.50007	-0.06696
VLFreq	-0.29371	-0.01848	0.32108	-0.34892	0.02977	0.14488
Dstrength	0.06504	0.00832	-0.11776	-0.77359	0.10101	-0.08206
Fatigue	-0.39946	-0.28857	0.266	-0.29642	-0.22277	-0.29988
TESMAV	-0.12403	-0.07648	0.03527	-0.2613	0.53715	-0.10795
LESMaV	-0.5405	-0.4747	-0.16986	-0.02048	0.06437	-0.00463
VLMAV	0.34232	0.33146	0.37407	-0.34739	0.57465	0.16201
Duration	-0.02838	0.4508	-0.18113	0.67037	-0.03457	0.00519
PeakVertAcc	-0.22739	0.56404	-0.10187	0.66079	-0.09902	-0.11951
HandForce	-0.11024	0.90868	-0.06195	0.21782	0.01617	0.11394
PeakFlex	0.91642	-0.13825	0.06689	-0.22603	-0.00462	0.03945
PeakExtVel	0.24482	0.13557	0.31791	0.1441	0.28595	-0.64713
PeakShear	0.03968	0.86102	0.10251	0.21364	-0.03089	0.05969
PeakCom	0.08203	-0.06861	0.9463	0.02961	0.10028	-0.07877
PeakMom	0.00203	-0.04618	0.95624	-0.06467	0.01146	-0.01771
Imoment	0.00006	0.09554	0.08287	0.07428	0.132	0.77155
Flx	0.93755	-0.1432	0.09175	-0.14052	0.01022	0.00039
Knee	0.8712	0.07039	-0.11931	0.14681	0.00844	-0.25277

4.4.3.1 Canonical Correlation Analysis Results of Semi-squat Lifting Posture

Table 4.20 shows that canonical correlation analysis indicates, at $\alpha=0.05$ level, two (2) significant canonical variates that account for a significant proportion of variation in the data for both fatigue analysis parameters and for EMG amplitude, kinematic, and kinetic parameters. Significant canonical variates detected are labeled 1 and 2, in descending order of Cumulative R-Square value between VAR and WITH canonical variates. The cumulative R-Square values for canonical variates 1 and 2 displayed in Table 4.21 were 0.9913 and 0.9716, respectively.

4.4.3.1.1 VAR (Fatigue Analysis) Variables and the Canonical Variates

Table 4.21 indicates that canonical VAR variates 1 and 2 explain a total of 37.16% of the variation present in the original VAR variables and that WITH variates 1 and 2 share in commonly explaining 36.35% of that total variation. 12.42% of the variation in the original VAR variables is explained by canonical VAR variate 1. Table 4.22 shows that this canonical VAR variate 1 is highly loaded on the VAR variable thoracic erector spinae normalized EMG frequency (0.612) and possesses weak loadings on lumbar erector spinae normalized EMG frequency (-0.3942) and vastii lateralis normalized EMG frequency (0.3298). Canonical WITH variate 1, which accounts for 12.32% of the variation in the original VAR variables, is highly cross loaded on the VAR variable thoracic erector spinae normalized EMG frequency (0.6093), as can be observed in Table 4.23. Canonical VAR variate 2, which accounts for 24.73% of the variation present in the original VAR variables, was observed to load extremely highly on the VAR variable dynamic leglift floor to knuckle height strength (0.9504), moderately on thoracic erector spinae normalized EMG frequency (-0.4584) and subjective fatigue

rating (0.4378), and weakly on the VAR variable time (0.3437). Similarly, canonical WITH variate 2, which explains 24.03% of the variation in the original VAR variables, possessed extremely high loading on the VAR variable dynamic leglift floor to knuckle height strength (0.9368), moderate loadings on thoracic erector spinae normalized EMG frequency (-0.4518) and subjective fatigue rating (0.4316), and weak loading on the VAR variable time (0.3388).

4.4.3.1.2 WITH (EMG Amplitude, Kinematic, and Kinetic) Variables and the Canonical Variates

Canonical WITH variates 1 and 2 explain a total of 43.88% of the variation present in the original WITH variables and canonical VAR variates 1 and 2 share in commonly explaining 42.73% of that total variation. 5.08% of the variation in the original WITH variables is explained by canonical WITH variate 1, which is observed to load highly on WITH variable lumbar erector spinae normalized amplitude (-0.6373). Likewise, canonical VAR variate 1 accounts for 5.04% of the variation in the original WITH variables and is seen to load highly on WITH variable lumbar erector spinae normalized amplitude (-0.6345). Canonical WITH variate 2 accounted for 38.8% of the total variation of the original WITH variables and loaded highly on the WITH variables peak lumbosacral/trunk extension velocity (0.8702), duration of lift cycle (0.8537), peak vertical acceleration of the load (0.8445), average force on hands (0.8287), peak lumbosacral flexion (-0.7763), peak lumbosacral shear force (0.766), and lumbosacral flexion angle at initiation of lift (-0.7613); moderately on WITH variables thoracic erector spinae normalized EMG amplitude (-0.5968) and peak lumbosacral compressive force (0.4362); and weakly on WITH variable peak lumbosacral moment (0.3237). Canonical VAR variate 2, which accounts for 37.69% of the total variation in the original

WITH variables was similarly observed to load highly on the WITH variables peak lumbosacral/trunk extension velocity (0.8578), duration of lift cycle (0.8415), peak vertical acceleration of the load (0.8324), average force on hands (0.8169), peak lumbosacral flexion (-0.7652), peak lumbosacral shear force (0.7551), and lumbosacral flexion angle at initiation of lift (-0.7504); moderately on WITH variables thoracic erector spinae normalized EMG amplitude (-0.5882) and peak lumbosacral compressive force (0.4265); and weakly on WITH variable peak lumbosacral moment (0.319).

Table 4.20 Summary of canonical correlation test statistics for semi-squat posture (Significant p-values at $\alpha=.05$ level are displayed as bold. Marginally significant p-values $[.05 < \alpha < 1]$ are displayed as italicized.)

Test of H_0 : The Canonical Correlation in the current row and all that follow are zero				
Likelihood Ratio	F Value	Numerator DF	Denominator DF	Pr>F
1.05E-06	3.69	84	28.671	0.0001
0.000121	2.44	65	27.573	0.0057
0.004249	1.64	48	25.151	0.0915
0.044073	1.22	33	21.327	0.3206
0.188092	1.04	20	16	0.4709
0.504286	0.98	9	9	0.51

Table 4.21 Summary of standardized variance of the original variables explained by the canonical variates for semi-squat posture.

Standardized Variance of the VAR Variables Explained by					
	Their own canonical variates			The opposite canonical variates	
Canonical Variate Number	Proportion	Cumulative Proportion	Cumulative R-Square	Proportion	Cumulative Proportion
1	0.1242	0.1242	0.9913	0.1232	0.1232
2	0.2473	0.3716	0.9716	0.2403	0.3635
3	0.0877	0.4593	0.9036	0.0792	0.4427
4	0.1957	0.6549	0.7657	0.1498	0.5925
5	0.1781	0.833	0.627	0.1117	0.7042
6	0.167	1	0.4957	0.0828	0.787
Standardized Variance of the WITH Variables Explained by					
	Their own canonical variates			The opposite canonical variates	
Canonical Variate Number	Proportion	Cumulative Proportion	Cumulative R-Square	Proportion	Cumulative Proportion
1	0.0508	0.0508	0.9913	0.0504	0.0504
2	0.388	0.4388	0.9716	0.3769	0.4273
3	0.0936	0.5324	0.9036	0.0845	0.5119
4	0.0642	0.5965	0.7657	0.0491	0.561
5	0.0614	0.6579	0.627	0.0385	0.5995
6	0.0433	0.7013	0.4957	0.0215	0.621

Table 4.22 Summary of canonical loadings between investigated variables and their canonical variates for semi-squat posture. (Strong loadings are displayed as bold. Moderate to weak loadings are displayed as italicized.)

Correlations Between the VAR Variables and Their Canonical Variates		
	V1	V2
Time	-0.0517	0.3437
TESFreq	0.612	-0.4584
LESFreq	-0.3942	0.2074
VLFreq	0.3298	-0.1329
Dstrength	0.1991	0.9504
Fatigue	0.2538	0.4378
Correlations Between the WITH Variables and Their Canonical Variates		
	W1	W2
TESMAV	-0.2806	-0.5968
LESMaV	-0.6373	0.0016
VLMAV	0.1581	-0.2603
Duration	0.0369	0.8537
PeakVertAcc	-0.0362	0.8445
HandForce	-0.1513	0.8287
PeakFlex	0.2079	-0.7763
PeakExtVel	-0.128	0.8702
PeakShear	-0.2169	0.766
PeakCom	0.0325	0.4326
PeakMom	0.1114	0.3237
Imoment	0.0633	0.0558
Flx	0.0193	-0.7613
Knee	-0.2276	0.2398

Table 4.23 Summary of canonical cross loadings between fatigue analysis variables and the electromyography amplitude, kinematic, and kinetic variates for semi-squat posture. (Strong loadings are displayed as bold. Moderate to weak loadings are displayed as italicized.)

Correlations Between the VAR Variables and the Canonical Variates of the WITH Variables		
	W1	W2
Time	-0.0514	<i>0.3388</i>
TESFreq	0.6093	<i>-0.4518</i>
LESFreq	<i>-0.3925</i>	0.2044
VLFreq	<i>0.3284</i>	-0.131
Dstrength	0.1982	0.9368
Fatigue	<i>0.2527</i>	<i>0.4316</i>

Table 4.24 Summary of canonical cross loadings between electromyography amplitude, kinematic, and kinetic variables and the fatigue analysis variates for semi-squat posture. (Strong loadings are displayed as bold. Moderate to weak loadings are displayed as italicized.)

Correlations Between the WITH Variables and the Canonical Variates of the VAR Variables		
	V1	V2
TESMAV	-0.2794	-0.5882
LESMAV	-0.6345	0.0016
VLMAV	0.1574	-0.2566
Duration	0.0367	0.8415
PeakVertAcc	-0.0361	0.8324
HandForce	-0.1506	0.8169
PeakFlex	0.207	-0.7652
PeakExtVel	-0.1275	0.8578
PeakShear	-0.2159	0.7551
PeakCom	0.0324	0.4265
PeakMom	0.1109	0.319
Imoment	0.063	0.055
Flx	0.0192	-0.7504
Knee	-0.2266	0.2364

4.4.3.2 Canonical Correlation Analysis Results of Semi-stoop Lifting Posture

Table 4.25 shows that canonical correlation analysis indicates, at $\alpha=0.05$ level, two (2) significant canonical variates that accounts for a significant proportion of variation in the data for both fatigue analysis parameters and for EMG amplitude, kinematic, and kinetic parameters. The significant canonical variates detected are labeled variates 1 and 2 for VAR and WITH. The cumulative R-Square values for canonical variates 1 and 2, displayed in Table 4.26 were 0.9661 and 0.9302, respectively.

4.4.3.2.1 VAR (Fatigue Analysis) Variables and the Canonical Variates

Table 4.26 indicates that canonical VAR variates 1 and 2 explain a total of 50.66% of the variation present in the original VAR variables and that WITH variate 1 shares in commonly explaining 48.29% of that total variation. Table 4.27 shows that this canonical VAR variate 1 is highly loaded on the VAR variables dynamic leglift floor to knuckle height strength (-0.9713), subjective fatigue rating (0.7149), and lumbar erector spinae normalized EMG frequency (0.6697). Canonical WITH variate 1, which accounts for 31.39% of the variation in the original VAR variables, is similarly highly cross loaded on the VAR variables dynamic leglift floor to knuckle height strength (-0.9547), subjective fatigue rating (0.7027), and lumbar erector spinae normalized EMG frequency (0.6583), as can be observed in Table 4.28. Canonical VAR variate 2, which accounts for 18.17% of the variation present in the original VAR variables, was observed to load highly on the VAR variable thoracic erector spinae normalized EMG frequency (0.7956) and moderately on VAR variable subjective fatigue rating (0.4017). Similarly, canonical WITH variate 2, which explains 16.91% of the variation in the original VAR variables,

possessed high loading on the VAR variable thoracic erector spinae normalized EMG frequency (0.7673) and weak loading on VAR variable subjective fatigue rating (0.3874).

4.4.3.2.2 WITH (EMG Amplitude, Kinematic, and Kinetic) Variables and the Canonical Variates

Canonical WITH variates 1 and 2 explain a total of 35.57% of the variation present in the original WITH variables and canonical VAR variates 1 and 2 share in commonly explaining 34.18% of that total variation. 30.59% of the variation in the original WITH variables is explained by canonical WITH variate 1, which is observed to load highly on WITH variables peak lumbosacral moment (0.9128), peak lumbosacral compressive force (0.8829), peak lumbosacral flexion (0.8008), duration of lift cycle (-0.7008), lumbosacral flexion angle at initiation of lift (0.7002), average force on hands (-0.6157), and peak vertical acceleration of the load (-0.6086); and to load weakly on the WITH variable vastii lateralis normalized EMG amplitude (0.3749). Likewise, canonical VAR variate 1 accounts for 29.55% of the variation in the original WITH variables and is seen to load highly on WITH variables peak lumbosacral moment (0.8972), peak lumbosacral compressive force (0.8678), peak lumbosacral flexion (0.7871), duration of lift cycle (-0.6888), lumbosacral flexion angle at initiation of lift (0.6882), and average force on hands (-0.6052); moderately on WITH variable peak vertical acceleration of the load (-0.5965); and to load weakly on the WITH variable vastii lateralis normalized EMG amplitude (0.3685). Canonical WITH variate 2 accounted for 4.98% of the total variation of the original WITH variables and loaded highly on the WITH variable knee flexion angle at initiation of lift (0.6058) and weakly on WITH variable lumbar erector spinae normalized EMG amplitude (0.3939). Canonical VAR variate 2, which accounts for 4.63% of the total variation in the original WITH variables, was similarly observed to

load moderately on the WITH variable knee flexion angle at initiation of lift (0.5843) and weakly on WITH variable lumbar erector spinae normalized EMG amplitude (0.3799).

Table 4.25 Summary of canonical correlation test statistics for semi-stoop posture (Significant p-values at $\alpha=.05$ level are displayed as bold.)

Test of H_0 : The Canonical Correlation in the current row and all that follow are zero				
Likelihood Ratio	F Value	Numerator DF	Denominator DF	Pr>F
4.82E-05	2.67	84	45.392	0.0002
0.001424	1.93	65	41.75	0.0126
0.020398	1.34	48	36.708	0.1822
0.136174	0.88	33	30.166	0.636
0.38677	0.67	20	22	0.8152
0.677592	0.63	9	12	0.7492

4.4.3.3 Canonical Correlation Analysis Results of Stoop Lifting Posture

Table 4.30 shows that canonical correlation analysis indicates, at $\alpha=0.05$ level, one (1) significant canonical variate that accounts for a significant proportion of variation in the data for both fatigue analysis parameters and for EMG amplitude, kinematic, and kinetic parameters. Significant canonical variates detected are labeled variate 1 for VAR and WITH canonical variables. The cumulative R-Square value for canonical variates 1 displayed in Table 4.31 was 0.9968.

4.4.3.3.1 VAR (fatigue analysis) variables and the Canonical Variate

Table 4.31 indicates that canonical VAR variate 1 explains a total of 37.87% of the variation present in the original VAR variables and that WITH variate 1 shares in

Table 4.26 Summary of standardized variance of the original variables explained by the canonical variates for semi-stoop posture.

Standardized Variance of the VAR Variables Explained by					
	Their own canonical variates			The opposite canonical variates	
Canonical Variate Number	Proportion	Cumulative Proportion	Cumulative R-Square	Proportion	Cumulative Proportion
1	0.3249	0.3249	0.9661	0.3139	0.3139
2	0.1817	0.5066	0.9302	0.1691	0.4829
3	0.1777	0.6843	0.8502	0.151	0.634
4	0.1185	0.8028	0.6479	0.0768	0.7108
5	0.1634	0.9662	0.4292	0.0701	0.7809
6	0.0338	1	0.3224	0.0109	0.7918
Standardized Variance of the WITH Variables Explained by					
	Their own canonical variates			The opposite canonical variates	
Canonical Variate Number	Proportion	Cumulative Proportion	Cumulative R-Square	Proportion	Cumulative Proportion
1	0.3059	0.3059	0.9661	0.2955	0.2955
2	0.0498	0.3557	0.9302	0.0463	0.3418
3	0.1232	0.4789	0.8502	0.1048	0.4466
4	0.0347	0.5136	0.6479	0.0225	0.4691
5	0.0676	0.5812	0.4292	0.029	0.4981
6	0.0761	0.6573	0.3224	0.0245	0.5226

Table 4.27 Summary of canonical loadings between investigated variables and their canonical variates for semi-stoop posture. (Strong loadings are displayed as bold. Moderate to weak loadings are displayed as italicized.)

Correlations Between the VAR Variables and Their Canonical Variates		
	V1	V2
Time	-0.0633	0.3098
TESFreq	0.1389	0.7956
LESFreq	0.6697	-0.3135
VLFreq	-0.1515	-0.2957
Dstrength	-0.9713	-0.1202
Fatigue	0.7149	0.4017
Correlations Between the WITH Variables and Their Canonical Variates		
	W1	W2
TESMAV	0.2682	0.0044
LESMaV	-0.0077	0.3939
VLMAV	0.3749	-0.0551
Duration	-0.7008	0.0215
PeakVertAcc	-0.6068	0.2164
HandForce	-0.6157	0.0105
PeakFlex	0.8008	0.1973
PeakExtVel	0.1199	0.0423
PeakShear	-0.2489	0.2326
PeakCom	0.8829	0.0403
PeakMom	0.9128	-0.0599
Imoment	0.0959	0.0992
Flx	0.7002	0.1219
Knee	0.038	0.6058

Table 4.28 Summary of canonical cross loadings between fatigue analysis variables and the electromyography amplitude, kinematic, and kinetic variates for semi-stoop posture. (Strong loadings are displayed as bold. Moderate to weak loadings are displayed as italicized.)

Correlations Between the VAR Variables and the Canonical Variates of the WITH Variables		
	W1	W2
Time	-0.0623	0.2988
TESFreq	0.1365	0.7673
LESFreq	0.6583	-0.3024
VLFreq	-0.1489	-0.2852
Dstrength	-0.9547	-0.1159
Fatigue	0.7027	0.3874

Table 4.29 Summary of canonical cross loadings between electromyography amplitude, kinematic, and kinetic variables and the fatigue analysis variates for semi-stoop posture. (Strong loadings are displayed as bold. Moderate to weak loadings are displayed as italicized.)

Correlations Between the WITH Variables and the Canonical Variates of the VAR Variables		
	V1	V2
TESMAV	0.2636	0.0043
LESMAV	-0.0076	<i>0.3799</i>
VLMAV	<i>0.3685</i>	-0.0531
Duration	-0.6888	0.0207
PeakVertAcc	-0.5965	0.2087
HandForce	-0.6052	0.0101
PeakFlex	0.7871	0.1903
PeakExtVel	0.1178	0.0408
PeakShear	-0.2446	0.2243
PeakCom	0.8678	0.0389
PeakMom	0.8972	-0.0578
Imoment	0.0942	0.0957
Flx	0.6882	0.1176
Knee	0.0374	<i>0.5843</i>

commonly explaining 37.74% of that total variation. Table 4.32 shows that this canonical VAR variate 1 is highly loaded on the VAR variables dynamic leglift floor to knuckle height strength (-0.9431), subjective fatigue rating (0.8666), and thoracic erector spinae normalized EMG frequency (0.6439). Canonical WITH variate 1 is similarly highly cross loaded on the VAR variables dynamic leglift floor to knuckle height strength (-0.9416), subjective fatigue rating (0.8652), and thoracic erector spinae normalized EMG frequency (0.6428), as can be observed in Table 4.33.

4.4.3.3.2 WITH (EMG Amplitude, Kinematic, and Kinetic) Variables and the Canonical Variates

Canonical WITH variate 1 explains a total of 12.43% of the variation present in the original WITH variables and canonical VAR variate 1 shares in commonly explaining 12.39% of that total variation. Canonical WITH variate 1 is observed to load highly on WITH variable peak lumbosacral flexion (0.7319); moderately on WITH variables peak vertical acceleration of the load (-0.5831), duration of lift cycle (-0.53), and lumbosacral flexion angle at initiation of lift (0.4301); and weakly on WITH variables lumbar erector spinae normalized EMG amplitude (0.355) and knee flexion angle at initiation of lift (-0.3201). Likewise, canonical VAR variate 1 is seen to load highly on WITH variable peak lumbosacral flexion (0.7307); moderately on WITH variables peak vertical acceleration of the load (-0.5821), duration of lift cycle (-0.5292), and lumbosacral flexion angle at initiation of lift (0.4294); and weakly on WITH variables lumbar erector spinae normalized EMG amplitude (0.3544) and knee flexion angle at initiation of lift (-0.3195).

Table 4.30 Summary of canonical correlation test statistics for stoop posture
(Significant p-values at $\alpha=.05$ level are displayed as bold.)

Test of H_0 : The Canonical Correlation in the current row and all that follow are zero				
Likelihood Ratio	F Value	Numerator DF	Denominator DF	Pr>F
1.68E-06	2.71	84	23.097	0.0042
0.000524	1.39	65	22.847	0.1938
0.008231	1.1	48	21.299	0.4187
0.0677	0.83	33	18.381	0.686
0.439017	0.36	20	14	0.9825
0.730348	0.33	9	8	0.9414

Table 4.31 Summary of standardized variance of the original variables explained by the canonical variates for stoop posture.

Standardized Variance of the VAR Variables Explained by					
	Their own canonical variates			The opposite canonical variates	
Canonical Variate Number	Proportion	Cumulative Proportion	Cumulative R-Square	Proportion	Cumulative Proportion
1	0.3787	0.3787	0.9968	0.3774	0.3774
2	0.2151	0.5938	0.9363	0.2014	0.5789
3	0.1105	0.7043	0.8784	0.097	0.6759
4	0.0628	0.7671	0.8458	0.0531	0.729
5	0.1543	0.9213	0.3989	0.0615	0.7906
6	0.0787	1	0.2697	0.0212	0.8118
Standardized Variance of the WITH Variables Explained by					
	Their own canonical variates			The opposite canonical variates	
Canonical Variate Number	Proportion	Cumulative Proportion	Cumulative R-Square	Proportion	Cumulative Proportion
1	0.1243	0.1243	0.9968	0.1239	0.1239
2	0.1327	0.257	0.9363	0.1243	0.2482
3	0.1571	0.4141	0.8784	0.138	0.3862
4	0.122	0.5361	0.8458	0.1032	0.4894
5	0.0616	0.5978	0.3989	0.0246	0.514
6	0.0547	0.6524	0.2697	0.0147	0.5287

Table 4.32 Summary of canonical loadings between investigated variables and their canonical variates for stoop posture. (Strong loadings are displayed as bold. Moderate to weak loadings are displayed as italicized.)

Correlations Between the VAR Variables and Their Canonical Variates	
	V1
Time	0.0266
TESFreq	0.6439
LESFreq	0.0086
VLFreq	<i>0.4649</i>
Dstrength	-0.9431
Fatigue	0.8666
Correlations Between the WITH Variables and Their Canonical Variates	
	W1
TESMAV	0.112
LESMASV	<i>0.355</i>
VLMAV	0.1316
Duration	<i>-0.53</i>
PeakVertAcc	<i>-0.5831</i>
HandForce	0.2293
PeakFlex	0.7319
PeakExtVel	0.1918
PeakShear	0.0815
PeakCom	-0.0603
PeakMom	0.0287
Imoment	0.1999
Flx	<i>0.4301</i>
Knee	<i>-0.3201</i>

Table 4.33 Summary of canonical cross loadings between fatigue analysis variables and the electromyography amplitude, kinematic, and kinetic variates for stoop posture. (Strong loadings are displayed as bold.)

Correlations Between the VAR Variables and the Canonical Variates of the WITH Variables	
	W1
Time	0.0266
TESFreq	0.6428
LESFreq	0.0086
VLFreq	0.4641
Dstrength	-0.9416
Fatigue	0.8652

Table 4.34 Summary of canonical cross loadings between electromyography amplitude, kinematic, and kinetic variables and the fatigue analysis variates for stoop posture. (Strong loadings are displayed as bold. Moderate to weak loadings are displayed as italicized.)

Correlations Between the WITH Variables and the Canonical Variates of the VAR Variables	
	V1
TESMAV	0.1119
LESMaV	0.3544
VLMAV	0.1314
Duration	-0.5292
PeakVertAcc	-0.5821
HandForce	0.2289
PeakFlex	0.7307
PeakExtVel	0.1915
PeakShear	0.0814
PeakCom	-0.0602
PeakMom	0.0286
Imoment	0.1996
Flx	0.4294
Knee	-0.3195

4.4.4 Principal Factors Analysis Results According to Lifting Posture

Once the data was divided into individual lifting postures selected, separate principal factors analyses were performed on the data of the subject pool for each posture to indicate the principal “factors” which accounted for the variance in the data and to detect any correlation among the fatigue analysis, electromyography amplitude, kinematic, and kinetic parameters during freestyle lifting under each posture.

4.4.4.1 Principal Factors Analysis Results of Semi-squat Lifting Posture

Utilizing the Kaiser criterion, principal factors analysis detected six (6) factors, which retained eigenvalues greater than 1 and accounted for the majority of the variation in the semi-squat freestyle lifting data. Factors detected are indicated as Factors 1-6 and are presented in the order of greatest to least amount of variance accounted for. Standardized variance explained by each factor and principal components correlation coefficient results are given in Tables 4.35 and 4.36, respectively.

The results are as follows:

- Factor 1 accounted for the greatest amount of variance in the original data, yielding an eigenvalue of 7.772839. Factor 1 possessed high loadings on original variables average force on hands (0.96209), peak lumbosacral flexion (-0.94312), peak lumbosacral shear force (0.92443), lumbosacral flexion at initiation of lift (-0.91286), peak vertical acceleration of load (0.90865), duration of lift cycle (0.88697), lumbar erector spinae normalized amplitude (0.85419), peak lumbosacral/trunk extension velocity (0.75593), and thoracic erector spinae normalized frequency (-0.71079); moderate loadings on variables dynamic leglift floor to knuckle height strength (-

0.56855) and knee angle at initiation of lift (0.44974); and weak loadings on variable thoracic erector spinae normalized amplitude (-0.36898).

- Factor 2 yielded an eigenvalue of 2.350213, accounting for a considerably lesser amount of the variance in the original data. Factor 2 loaded highly on variables time (0.89757) and vastii lateralis normalized EMG amplitude (0.89599), moderately on variable lumbar erector spinae normalized EMG amplitude (0.4164), and weakly on variable peak lumbosacral/trunk extension velocity (0.32567).
- With an eigenvalue of 2.242271, Factor 3 loaded extremely highly on original variables peak lumbosacral moment (0.943) and compressive force (0.92385).
- An eigenvalue of 1.830736 was associated with Factor 4. High factorial loadings were observed for Factor 4 on variables vastii lateralis normalized EMG frequency (0.89956) and thoracic erector spinae normalized EMG amplitude (-0.63008), and moderate loading was observed on the variable knee angle at initiation of lift (-0.54515).
- Factor 5 yielded an eigenvalue of 1.788788 and loaded highly on the original variables subjective fatigue rating (0.8017) and integrated lumbosacral moment (-0.73873). Moderate loading was observed on variable lumbar erector spinae normalized EMG frequency (0.51145).
- Factor 6 returned an eigenvalue of 1.508063 and loaded highly on variables lumbar erector spinae normalized EMG frequency (0.70535) and dynamic leglift floor to knuckle height strength (-0.62818). Moderate factorial loading was observed on original variables thoracic erector spinae normalized frequency (0.45825) and amplitude (-0.44948).

Table 4.35 Summary of eigenvalues for principal factors analysis factors detected for semi-squat posture.

Variance Explained by Each Factor					
Factor1	Factor2	Factor3	Factor4	Factor5	Factor6
7.772839	2.350213	2.242271	1.830736	1.788788	1.508063

Table 4.36 Summary of principal factors analysis factorial loadings between original variables and corresponding factors for semi-squat posture. (Strong loadings are displayed as bold. Moderate to weak loadings are displayed as italicized.)

Rotated Factor Pattern						
	Factor1	Factor2	Factor3	Factor4	Factor5	Factor6
Time	-0.0336	0.89757	0.31308	0.0079	0.00853	0.15807
TESFreq	-0.71079	0.11592	-0.03836	0.10465	-0.2035	0.45825
LESFreq	-0.20239	0.30172	0.04593	-0.05429	0.51145	0.70535
VLFreq	-0.21683	0.06855	0.04103	0.89956	0.15452	-0.09486
Dstrength	-0.56855	-0.00973	0.25338	0.18597	0.14705	-0.62818
Fatigue	0.09726	0.00615	0.08525	-0.1738	0.8017	0.09601
TESMAV	-0.36898	0.30908	-0.17236	-0.63008	0.15784	-0.44948
LESMaV	0.85419	0.4164	0.08756	-0.02435	-0.11258	-0.11202
VLMAV	0.20117	0.89599	0.16191	0.04647	-0.11858	-0.00215
Duration	0.88697	0.19437	0.18364	-0.09674	-0.14083	0.08935
PeakVertAcc	0.90865	0.07518	0.01678	-0.25429	-0.05441	0.03999
HandForce	0.96209	-0.03109	0.13042	-0.12608	0.10371	0.10115
PeakFlex	-0.94312	0.10961	-0.05289	-0.06312	-0.06881	-0.02703
PeakExtVel	0.75593	0.32567	0.31259	-0.19297	0.26588	0.11711
PeakShear	0.92443	-0.05268	0.2358	-0.10153	0.04678	0.20541
PeakCom	0.20406	0.22788	0.92385	-0.01969	0.06777	0.00738
PeakMom	0.09377	0.19932	0.943	0.06011	0.01154	-0.05913
Imoment	0.00875	0.13827	0.02451	-0.23111	-0.73873	0.07934
Flx	-0.91286	0.04814	0.11593	-0.21671	0.0406	0.11159
Knee	0.44974	-0.29193	0.20004	-0.54515	0.28739	0.2223

4.4.4.2 Principal Factors Analysis Results of Semi-stoop Lifting Posture

Utilizing the Kaiser criterion, principal factors analysis detected five (5) factors, which retained eigenvalues greater than 1 and accounted for the majority of the variation in the semi-stoop freestyle lifting data. Factors detected are indicated as Factors 1-5 and are presented in the order of greatest to least amount of variance accounted for. Standardized variance explained by each factor and principal factors correlation coefficient results are given in Tables 4.37 and 4.38, respectively.

The results are as follows:

- Factor 1 accounted for the greatest amount of variance in the original data, yielding an eigenvalue of 7.244742. Factor 1 possessed high loadings on original variables peak lumbosacral compressive force (0.93776), peak lumbosacral moment (0.93531), lumbar erector spinae normalized EMG amplitude (-0.91778), peak lumbosacral flexion (0.88814), lumbosacral flexion angle at initiation of lift (0.82774), average force on hands (-0.75331), peak vertical acceleration of load (-0.75272), duration of lift cycle (-0.73677), vastii lateralis normalized EMG amplitude (0.7311), and subjective fatigue rating (0.68481); while loading moderately on factor thoracic erector spinae normalized frequency (0.41861).
- Factor 2 yielded an eigenvalue of 2.976731. Factor 2 loaded highly on variables vastii lateralis normalized EMG frequency (-0.77778), knee angle at initiation of lift (0.74673), time (0.69981), and thoracic erector spinae normalized frequency (0.66609); moderately on variables subjective fatigue rating (-0.41552) and lumbosacral flexion at initiation of lift (0.40152); and weakly on variables, vastii

lateralis normalized EMG amplitude (0.36137), lumbar erector spinae normalized EMG frequency (0.33777), and peak lumbosacral flexion (0.32162).

- With an eigenvalue of 2.495221, Factor 3 loaded highly on original variables peak lumbosacral shear (0.84338), integrated lumbosacral moment (0.76558), and peak lumbosacral/trunk extension velocity (0.72433). Moderate loading was observed in Factor 3 on variable average force on hands (0.55441), while weak loading was observed on variable peak vertical acceleration of load (0.38021).
- An eigenvalue of 1.748851 was associated with Factor 4. High factorial loading was observed for Factor 4 on variable thoracic erector spinae normalized EMG amplitude (0.89172). Moderate factorial loadings was seen for Factor 4 on variable time (0.54731), while weak loadings were seen on variables lumbar erector spinae normalized frequency (0.39233), knee angle at initiation of lift (-0.33508), and peak vertical acceleration of load (-0.32212).
- Factor 5 yielded an eigenvalue of 1.614568 and loaded highly on the original variables dynamic leglift floor to knuckle height strength (0.87508) and lumbar erector spinae normalized frequency (0.63162). Weak loading was observed on variable knee flexion angle at initiation of lift (0.31563).

Table 4.37 Summary of eigenvalues for principal factors analysis factors detected for semi-stoop posture.

Variance Explained by Each Factor				
Factor1	Factor2	Factor3	Factor4	Factor5
7.244742	2.976731	2.495221	1.748851	1.614568

Table 4.38 Summary of principal factors analysis factorial loadings between original variables and corresponding factors for semi-stoop posture. (Strong loadings are displayed as bold. Moderate to weak loadings are displayed as italicized.)

Rotated Factor Pattern					
	Factor1	Factor2	Factor3	Factor4	Factor5
Time	0.08987	0.69981	-0.06658	0.54731	0.13302
TESFreq	0.41861	0.66609	-0.2549	0.14662	-0.06004
LESFreq	0.16574	0.33777	-0.01312	0.39233	0.63162
VLFreq	0.27059	-0.77778	0.10733	-0.01099	0.2496
Dstrength	0.08446	-0.11507	0.05752	-0.18167	0.87508
Fatigue	0.68481	-0.41552	0.17438	0.10246	-0.21805
TESMAV	-0.04869	-0.02669	-0.07008	0.89172	-0.0787
LESMASV	-0.91778	0.03705	0.03207	0.07681	-0.13246
VLMAV	0.7311	0.36137	0.1302	0.23396	0.20435
Duration	-0.73677	0.29414	-0.10657	-0.27927	-0.1706
PeakVertAcc	-0.75272	0.07584	0.38021	-0.32212	0.00573
HandForce	-0.75331	-0.16645	0.55441	-0.02821	-0.02941
PeakFlex	0.88814	0.32162	-0.02379	-0.08338	0.17474
PeakExtVel	0.15283	0.01887	0.72433	0.10794	-0.17231
PeakShear	-0.37648	-0.058	0.84338	-0.1356	0.09112
PeakCom	0.93776	0.07764	0.04971	-0.08829	0.02927
PeakMom	0.93531	-0.07581	0.06523	-0.10358	0.00056
Imoment	0.11499	-0.21903	0.76558	-0.13116	0.22367
Flx	0.82774	0.40152	-0.25135	-0.08317	0.06469
Knee	0.14864	0.74673	0.04141	-0.33508	0.31563

4.4.4.3 Principal Factors Analysis Results of Stoop Lifting Posture

Utilizing the Kaiser criterion, principal factors analysis detected five (5) factors, which retained eigenvalues greater than 1 and accounted for the majority of the variation in the stoop freestyle lifting data. Factors detected are indicated as Factors 1-5 and are presented in the order of greatest to least amount of variance accounted for. Standardized variance explained by each factor and principal components correlation coefficient results are given in Tables 4.39 and 4.40, respectively.

The results are as follows:

- Factor 1 accounted for the greatest amount of variance in the original data, yielding an eigenvalue of 4.558563. Factor 1 possessed high loadings on original variables average force on hands (0.9392), peak lumbosacral shear force (0.93233), knee angle at initiation of lift (-0.7951), peak lumbosacral/trunk extension velocity (-0.76148), and duration of lift cycle (0.67256). Moderate loadings were observed on factors lumbar erector spinae normalized frequency (-0.56706) and peak vertical acceleration of load (0.50145), and weak loadings were observed on factors thoracic erector spinae normalized frequency (-0.35452) and integrated lumbosacral moment (0.33081).
- Factor 2 yielded an eigenvalue of 4.13955, accounting for a considerable amount of the variance in the original data. Factor 2 loaded highly on variables lumbar erector spinae normalized EMG amplitude (-0.87592), peak lumbosacral flexion (0.82452), vastii lateralis normalized EMG amplitude (0.82054), peak vertical acceleration of load (-0.64693), lumbosacral flexion at initiation of lift (0.62111), dynamic leglift floor to knuckle height strength (0.62059) and duration of lift cycle (-0.61107);

moderately on variable thoracic erector spinae normalized amplitude (0.43015); and weakly on variable lumbar erector spinae normalized frequency (0.37921).

- With an eigenvalue of 2.518806, Factor 3 loaded extremely highly on original variables peak lumbosacral moment (0.95975) and compressive force (0.94466). Moderate loading was observed in Factor 3 on variable dynamic leglift floor to knuckle height strength (-0.55305), while weak loading was observed on variable thoracic erector spinae normalized EMG frequency (0.34774).
- An eigenvalue of 2.381154 was associated with Factor 4. High factorial loadings were observed for Factor 4 on variables vastii lateralis normalized EMG frequency (0.88252) and thoracic erector spinae normalized EMG frequency (0.69686). Moderate factorial loadings were seen for Factor 4 on variables thoracic erector spinae normalized amplitude (0.46923) and lumbar erector spinae normalized EMG frequency (0.40991), while weak loadings were seen on variables integrated lumbosacral moment (0.36142), lumbosacral flexion at initiation of lift (0.36142), and peak lumbosacral/trunk extension velocity (0.33671).
- Factor 5 yielded an eigenvalue of 2.179471 and loaded highly on the original variables subjective fatigue rating (0.85075) and time (-0.74454). Moderate loadings were observed on variables integrated lumbosacral moment (-0.47092), dynamic leglift floor to knuckle height strength (0.40834), and peak lumbosacral/trunk extension velocity (0.4036).

Table 4.39 Summary of eigenvalues for principal factors analysis factors detected for stoop posture.

Variance Explained by Each Factor				
Factor1	Factor2	Factor3	Factor4	Factor5
4.558563	4.13955	2.518806	2.381154	2.179471

Table 4.40 Summary of principal factors analysis factorial loadings between original variables and corresponding factors for stoop posture. (Strong loadings are displayed as bold. Moderate to weak loadings are displayed as italicized.)

Rotated Factor Pattern					
	Factor1	Factor2	Factor3	Factor4	Factor5
Time	-0.27316	0.05113	-0.25212	0.22182	-0.74454
TESFreq	-0.35452	-0.00265	0.34774	0.69686	0.24177
LESFreq	-0.56706	0.37921	-0.04804	0.40991	-0.05373
VLFreq	0.0342	-0.05656	-0.08458	0.88252	-0.19951
Dstrength	-0.12132	0.62059	-0.55305	0.0908	0.40834
Fatigue	-0.23084	-0.05692	-0.15322	0.23945	0.85075
TESMAV	-0.06004	0.43015	0.23293	0.46923	0.11292
LESMAS	0.10807	-0.87592	0.09079	-0.23667	-0.18582
VLMAV	0.36419	0.82054	-0.06527	0.15146	-0.21385
Duration	0.67256	-0.61107	0.06157	0.03068	0.12365
PeakVertAcc	0.50145	-0.64693	0.22142	-0.17528	-0.00069
HandForce	0.9392	0.19342	0.04293	-0.14971	-0.18439
PeakFlex	0.1419	0.82452	0.18621	-0.12885	-0.09894
PeakExtVel	-0.76148	0.1273	0.09358	0.33671	0.4036
PeakShear	0.93233	-0.01552	0.09596	-0.04966	-0.05377
PeakCom	-0.03888	-0.01644	0.94466	0.06229	-0.01475
PeakMom	0.14259	0.05043	0.95975	0.08754	0.0703
Imoment	0.33081	0.13444	0.05425	0.36142	-0.47092
Flx	0.03237	0.62111	0.07041	-0.35588	-0.2653
Knee	-0.7951	-0.20916	-0.00676	-0.2818	-0.13521

CHAPTER 5

DISCUSSION

This study represents a methodology to determine the effects of progressive fatigue, during prolonged repetitive manual lifting, on kinematic and biomechanical force parameters thought to be highly associated with increased risk of LBD. The methods used in this study include electromyographic amplitude and frequency parameters, subjective fatigue rating scale, static and dynamic strength measures, kinematic parameters, and measures of biomechanical force imposed on the low back and hands during a two-hour bout of repetitive lifting. It is hypothesized that as individuals become fatigued by repetitive lifting tasks, changes in kinematic and biomechanical force parameters tend to incur, exposing the lifter to increased risk of injury. It is also hypothesized that there may be some discernable relationships between various measures used to indicate fatigue in repetitive manual lifting.

5.1 Postures Employed During Freestyle Lifting Trials

Many studies by different researchers have been performed analyzing differences between lifting postures in kinematic, biomechanical force, and maximum acceptable weight parameters, with largely consistent and repeatable results. Most studies have considered some combination of forms and variations of stoop (or backlift), squat (or leglift), and freestyle lifting postures in their evaluations. While stoop and squat lifting postures are usually well described in the literature, generally in terms of knee and back positions and angles, freestyle lifting posture is not. Characteristics of the stoop posture are generally described as nearly straight knees and a horizontal back, while those of a squat posture are described as bent knees and an almost vertical back. The description of

freestyle lifting posture is generally limited to the instruction given to participants of the study, that is the posture accompanying the method felt “most suitable” or “most natural” for the subject. The one study (Chaffin and Page, 1994) that offers a characteristic description of the freestyle lifting posture evaluated, for biomechanical modeling purposes, describes the posture as consisting of “knees slightly flexed and the torso nearly horizontal.”

Comparative studies (Kumar, 1984; Garg and Herrin, 1979) have reported that, with respect to methods employing freestyle and squat lifting postures, the method using the stoop posture yielded significantly lower physiological costs in terms of lower heart rate and energy expenditure rates. The squat posture was indicated as being the most physiologically costly with an intermediate level of physiological costs being attributed the freestyle method. In terms of subjective feeling, with respect to freestyle, squat, and stoop lifting, Kumar (1984) reported that participants rated the freestyle method as the “least tiring” of the three methods and felt that the “most tiring” method was the method employing the squat posture. Freestyle lifting method has also been observed (Garg *et al.*, 1983; Garg and Saxena, 1979) to yield a greater maximum allowable weight, utilizing the psychophysical method, than that obtained where the stoop posture is employed. While squat posture is commonly recommended as best for reduction of injury potential during lifting, the literature (van Dieen *et al.*, 2000) indicates that only studies using static linked segment models have predicted a significant reduction of back load when using the squat technique as opposed to the stoop technique. Further, in such studies, where the horizontal distance to the load was constant (Garg and Herrin, 1979; Ekholm, *et al.*, 1982) and the load was in front of the feet, as in the current study, or where the

same data were reanalyzed using a dynamic model (Lindbeck and Arborelius, 1991), there was no effect of technique. van Dieen and colleagues (2000) reported that in all dynamically analyzed studies reviewed, where loads were lifted from a position in front of the feet, the squat technique yielded either greater peak and cumulative back loads or loads which were not significantly different than those observed where a technique utilizing the stoop posture was employed.

In the present study, the freestyle lifting technique was used. As with previous studies utilizing this method, the participants were instructed to lift in the way that “felt most natural.” In the performance of the experimental task, participants were observed to employ one of three qualitatively different lifting postures under the freestyle lifting condition. The lifting postures observed were defined as semi-squat, semi-stoop, and stoop postures, and their quantitative descriptions can be viewed in Table 5.1. No true squat lifting posture was observed in this experiment. This finding was not surprising as the handles of the load to be lifted were placed a considerable distance (≥ 30 cm) in front of the feet of the participants.

Table 5.1 Summary of lifting postures observed under freestyle lifting condition during experiment

Posture	Trunk Inclination (degrees)	Included Knee Angle (degrees)	Number of Participants
Semi-squat	$30^{\circ} \lesssim 45^{\circ}$	$\lesssim 110^{\circ}$	3
Semi-stoop	$45^{\circ} \lesssim 65^{\circ}$	$110^{\circ} \lesssim 140^{\circ}$	4
Stoop	$\gtrsim 65^{\circ}$	$\gtrsim 140^{\circ}$	3

Analyses of variance of the angular variables defining lifting posture indicate that the three observed postures were, by at least one of the two measures, quantifiably

different. A significant difference ($p=0.0073$) in trunk inclination was apparent between semi-squat and stoop lifting postures, while the difference in trunk inclination between semi-squat and semi-stoop postures trended ($p=0.0834$) towards significance. There were significant (at 5% α -level) differences in included knee angle between all three lifting postures observed. This was an interesting finding as no such quantitative descriptions of freestyle lifting postures have been discovered in the literature. Throughout the experimental session, no participant was observed to qualitatively change posture employed in lifting strategy, though there was a substantial amount of within subject variability between measurements of trunk inclination and included knee angle.

5.2 Fatigue Assessment

The literature indicates that many of the previous studies that attempted to analyze lifting related factors with respect to fatigue have either not quantitatively analyzed or assessed fatigue or have used the condition of “complete exhaustion” to signify a fatigued state. Of the studies that did attempt to quantify measures of fatigue, most have either used only static measures (Lee *et al.*, 1989; Potvin and Norman, 1993) or only measures that would indicate some level of local muscular fatigue (Kim and Chang, 1995). The few studies (Petrofsky and Lind, 1978; Kim *et al.*, 1992; Sparto *et al.*, 1997) that have attempted to quantify or analyze measures of general physical fatigue employed only trained stoop or squat techniques in their respective experimental protocols. No study was discovered in which any psychophysical measure such as “subjective fatigue rating” was used to progressively quantify levels of fatigue.

Analyses of variance in this study supported our expectation that the lifting task was sufficient to induce some level of fatigue over time. Each participant exhibited at

least one measure of increased general physical fatigue as his respective lifting session progressed. Two participants were unable to complete the two-hour lifting session as a result of excessive fatigue. In the first case, the participant reported “a feeling of complete exhaustion” after 60 minutes of lifting and the lifting session was discontinued. In the second, during the final bout of lifting (> minute-105) it was the opinion of the investigator that the lifting session should be discontinued. In this case, the lifting session was discontinued and the final strength measurements were obtained. It should be noted that the psychophysically selected load masses (27.5 kg and 26.3 kg, respectively) of the two subjects who did not complete the two-hour lifting task were the greatest observed in the study. It is thus concluded that the inability of the subjects to complete the two-hour lifting task was a result of an overestimation of maximum acceptable weight limit (MAWL). The complete data obtained from the two subjects were found to be viable, as their exclusion from the analysis did not alter the quality or interpretation of the results. These data were thus included in the reported data as the analysis techniques used in the current study were not sensitive to the resultant truncation.

At the end of the lifting session, a significant ($p = 0.0184$) decrease of 20.7% in mean static composite strength was observed across the participant pool, as compared to that measured immediately prior to the first bout of repetitive lifting. Two subjects did not exhibit any significant change in static composite strength and, in one participant, static composite strength increased by 6%. We attribute this to interindividual differences in lifting techniques observed and to differences in the unique ways that participants may have experienced fatigue. These findings are in contrast with those of

Lee and colleagues (1989), who observed no significant decrease in lifting strength after two hours of lifting and lowering of a 15.9kg (35lb) load utilizing the squat technique. This contrast is believed to be due the differences in the demands of the experimental tasks in that, though the task in the current study required only lifting of the load, the load selected utilizing the psychophysical method more closely matched the respective lifting capacities of the participants, allowing for a more durable and repeatable measure of fatigue. Our findings are, however, in direct agreement with those of Potvin and Norman (1993), who observed a 17% decrease, with some interindividual difference, in maximum extensor moment (indicating decreased trunk strength) during isometric trunk MVC after two hours of repetitive lifting under freestyle conditions, where the loads to be lifted were selected individually, with respect to participant characteristics.

A significant ($p = 0.0237$) “time and posture” interaction was observed in dynamic floor to knuckle height leglift strength. This was believed to represent a true difference in the way that this variable behaved between cases where different lifting postures were observed, though MANOVA did not indicate any significant (at 5% α -level) overall effect of “time and posture” interaction. No significant change in dynamic floor to knuckle height leglift strength was observed where either the stoop or the semi-stoop posture was used. Significant increases were observed, however, where the semi-squat lifting posture was used between the initial measurement of dynamic floor to knuckle height leglift strength and those recorded at minute one hundred five (0.025) and at minute one hundred twenty (0.0024). We believe that this increase in dynamic lifting strength, seen only where the semi-squat lifting posture is observed, may be a result of the similarity in fatigue characteristics and demands between lifting techniques

employing semi-squat and squat postures. Previous studies (Lee et al., 1989; Kim et al., 1992), utilizing the squat lifting posture, have reported that lifting (load) acceleration significantly increased at the end of the respective two hour lifting tasks. Because the dynamic strength test utilized the true squat lifting technique, it is reasoned that if fatigue characteristics of lifting techniques employing semi-squat and squat postures are similar, a potential towards increased acceleration during an isokinetic test may present itself as an increased instantaneous force or strength measurement. This thought or reasoning is unique in that this is, to the author's knowledge, the first suggestion in the literature that discreet, qualifiable lifting postures assumed under freestyle conditions may affect lifting characteristics where forced lifting is maintained or attempted. This is important because it adds further question to the debate regarding the protective nature of "squat lifting," particularly after some level of fatigue attained lifting using a "modified squat" or semi-squat posture.

While it was observed that there were interindividual differences in the participant responses to each fatigue indicating measure, the overall most consistent measure observed was the subjective fatigue rating. A significant ($p < 0.0001$) increase in subjective fatigue rating was observed as time progressed. We believe that the consistency of this indicator is largely due to its psychophysical nature, in that it accounts for aspects of biomechanical, physiological, and psychological fatigue, and thereby is less sensitive to any one particular factor or to the lifting technique or posture employed. Use of the subjective fatigue rating instrument yielded results indicating that individuals experienced the "feeling" of general physical fatigue at different rates and to different extents during the lifting task, as can be observed in Figure5.1. This is the first time, to

the author's knowledge, that a psychophysical instrument of this nature has been used to attempt to progressively quantify levels fatigue, on a time-continuum, during repetitive lifting.

Figure 5.1 Subjective fatigue ratings of individual participants during the lifting task

A considerable amount of interindividual variability was observed in local muscular fatigue indicating parameters. There did not appear to be any generalizable trend apparent among all participants in behavior of the normalized EMG median frequency of any observed muscle group. While interindividual differences were apparent in all cases, the one muscle group whose mean value of normalized EMG median frequency across all participants revealed a marginal ($p = 0.0531$) effect of time was that of the vastii lateralis. An initial decrease was observed between the first measurement at minute fifteen and the second at minute thirty, followed by a general increase for the remainder of the lifting session, such that a marginal ($p = 0.0648$) increase was realized from minute thirty to minute one hundred twenty. This indicates a

general trend to use the legs (*vastii lateralis*) more, initially in the lifting session, then to “save” them by using them less and allowing the leg muscles to recover as the lifting session progresses. These findings are not in agreement with those of Petrofsky and Lind (1978) and Kim and colleagues (1992), who reported significant decreases in power density spectrum parameters of muscle groups observed. The predictable and readily verified local muscular fatigue observed in these studies can be attributed to the fact that they used specific trained and forced lifting postures and techniques. The findings of the current study are, however, greatly in agreement with those of Kim and Chung (1995) and Potvin and Norman (1993), where freestyle lifting tasks were performed. Kim and Chung (1995) observed a decreases in normalized mean power frequency in lumbar erector spinae muscles after two hours of lifting and lowering at a rate of 6 cycles per minute, but not at a rate of 3 lift cycles per minute. Potvin and Norman (1993) similarly observed a significant decrease in mean power frequency of the thoracic erector spinae muscle groups, but not in the lumbar erector spinae muscle groups after two hour of lifting. This can be attributed to the fluid nature and properties of freestyle lifting, whereas adjustments can be made to minimize local muscular fatigue and to limit overall fatigue (Sparto *et al.*, 1997), as the authors of the previous studies also reported vast amounts of interindividual differences in local muscular fatigue assessment parameters.

Overall, we successfully showed that the design of the experiment was sufficient to impose some level of general physical fatigue on the participants. It was apparent that participants fatigued differently with respect to time and ultimately at different levels in freestyle repetitive lifting. We observed that while measures of general physical fatigue indicated some progressive trends of fatigue over time, under the fluid nature of load

bearing and redistribution in freestyle lifting, these were not apparent in observing the measures of local muscular fatigue alone.

5.3 Kinematic And Biomechanical Force Analysis

The literature indicates, with vastly mixed results, that as an individual experiences fatigue during a repetitive lifting task or as an extended repetitive lifting task proceeds, the lifting strategy or technique utilized may change, possibly introducing factors which increase the individual's risk of low back disorder. Among the kinematic and biomechanical force parameters analyzed in this study, none were observed to provide any significant, generalizable trend for all subjects as the lifting task proceeded. Similarly to the results observed for the local muscular fatigue indicating variables, there was great interindividual variability in the behavior of the biomechanical and kinematic force parameters with respect to time. Further, significant within-participant variability was observed, such that changes in each parameter were observed to occur with each measurement, but with no apparent generalizable pattern.

Of the kinematic and biomechanical force parameters analyzed, the one variable whose mean value across all participants revealed a marginal ($p = 0.0658$) effect of time was normalized EMG mean absolute value of the lumbar erector spinae muscle groups. While interindividual differences were apparent, the mean of the normalized lumbar erector spinae EMG maximum mean absolute value exhibited a general increase in amplitude, beginning after the first measurement at minute fifteen and continuing until the completion of the task. The nature of the progressive increase in amplitude was such that a marginally ($p = 0.0559$) significant difference was observed between the initial measurement of the normalized lumbar erector spinae mean absolute value at minute

fifteen and that recorded at the conclusion of the experiment. This finding indicates a general trend of the low back to work harder or to work more as the lifting task proceeded. These findings are consistent with those of Potvin (1992), who reported no generalizable trends or changes in EMG or biomechanical loads imposed on the low back among all subjects after prolonged repetitive lifting, but a group mean decrease in EMG amplitude parameters of the vastii lateralis muscles was observed, indicating a trend towards more of a reliance on the trunk muscles and less on the legs as the lifting task proceeded.

In general, it was observed that no common trends were apparent for any kinematic or biomechanical force parameter for all participants across the study. Further, values associated with each variable observed varied greatly within trial across observations, indicating constant changes in lifting strategy or lifting technique. This observation further supports the idea that constant adjustments are made in freestyle lifting to minimize local muscular fatigue and to limit overall fatigue (Sparto et al., 1997). The constant nature of the variability of the kinematic and biomechanical force parameters observed here, were made apparent, in large part due to the periodic design of this study. It is clear that a study under which these variables were observed only at points in time designated as “before” and “after” fatigue would have yielded significantly different results.

5.4 Fatigue Inter-Parameter Relationships and Relevance to Freestyle Repetitive Lifting

Previous studies analyzing possible fatigue related changes in variables associated with repetitive manual lifting have analyzed variables of concern with respect to time or repetition only. The few studies that have analyzed lifting parameters with direct relation

to muscle fatigue or weakness have done so by inducing some level of local muscular fatigue or muscle weakness (in a manner other than repetitive lifting) and performing only “pre-fatigue/post-fatigue” examinations. As has been previously discussed in section 5.2, evidence of progressive fatigue resulting from a freestyle repetitive manual lifting task, indicated by at least one measure of general physical fatigue, was observed for each participant over time. Analysis of the variability present in fatigue indicating variables led us to conclude that while individuals may experience some level of fatigue in performing the task, under freestyle manual repetitive lifting conditions, individuals fatigue uniquely. Similar observations were made in the analysis of kinematic and biomechanical force parameters, with respect to time. We observed that individuals performed the lifting task using different lifting postures, techniques, and associated continuous and unique spontaneous adjustments. While these findings did lead us to conclude that there was no consistent, generalizable effect of time or repetition on kinematic or biomechanical force parameters, because individuals were observed to also fatigue uniquely, we did not feel that this was sufficient to conclude that there was no relationship between indices of fatigue and these parameters. For this reason, it was important to analyze observed kinematic and biomechanical force parameters directly in concert with fatigue indicating parameters to determine the existence and/or extent of any such relationships.

5.4.1 Inter-parameter Relationships of Entire Subject Pool

Canonical correlation analysis indicated that, in general, during the freestyle repetitive manual lifting task, the measure of subjective fatigue maintained a fairly strong positive relationship with observed peak forces imposed on the low back, specifically

peak moment and peak compressive and shear forces. That is, as subjects “felt” increasingly fatigued, that perception of increased fatigue tended to be accompanied by increased forces at the low back. This finding indicates that subjective feeling of fatigue during a repetitive lifting task under freestyle lifting conditions may be a fairly good predictor of possible changes in low back forces. Changes in dynamic floor to knuckle height leglift strength and, to a lesser extent, normalized EMG median frequency of the lumbar erector spinae also displayed some predictive power with respect to a number of kinematic and biomechanical force production parameters. It was observed that as the dynamic strength decreased and the low back fatigued, indicated by decreased median frequency of lumbar erector spinae EMG, EMG mean absolute values of the erector spinae muscle groups of the back tended to decrease, while peak vertical acceleration of the load, knee angle at the initiation of the lift, and the duration of the lift tended to increase. The indication of these findings is that, in general, as the dynamic strength of the individual decreased and the low back experienced progressive local muscular fatigue, the back as a whole tended to work with less maximal intensity; there tended to be a decrease in the amount of knee flexion; and a slower lift, characterized by an increased peak vertical acceleration tended to occur. A further, slightly less powerful, indicator of increase in peak vertical acceleration of the load was observed to be increased local muscular fatigue of the thoracic erector spinae muscle groups. It was observed that a decrease in median frequency of the thoracic erector spinae EMG was accompanied, in general, by an increase in peak vertical load acceleration.

Principal factors analysis indicated a number of interrelationships between the fatigue indicating variables and their relation to kinematic and/or biomechanical force

variables. Subjective fatigue rating and local muscular fatigue of the lumbar erector spinae muscle groups were seen to share some common factor, on which they both loaded (-0.39946 and -0.46787 , respectively) significantly. This factor was interpreted to be a largely postural factor, with respect to how hard the lower back worked, as moderate to extremely high loadings were observed on the normalized mean absolute value of the lumbar erector spinae (-0.5405), peak lumbosacral flexion angle (0.91642), and the lumbosacral flexion (0.93755) and included knee (0.8712) angles at the initiation of the lift. This finding stands largely to confirm the hypothesis that lifting posture, selected under freestyle lifting conditions, plays a significant role in how hard the low back works and in how the low back experiences local muscular fatigue. Further, we can conclude that postural factors, related to exertion and fatigue of the low back, has some role in the determination or individual interpretation of level of subjective fatigue.

A second factor was observed to be greatly shared by the parameters indicating local muscular fatigue of the back, such that normalized EMG median frequencies of thoracic and lumbar erector spinae muscle groups yielded loading factors of -0.71952 and -0.40317 , respectively. Extremely high loadings were observed on this factor by biomechanical force parameters average force on hands (0.90896) and peak lumbosacral shear force (0.86102); and a moderate loading (0.56404) by peak vertical load acceleration was observed. From this, it was seen that the variation in peak lumbosacral shear force and average force on the hands was almost exclusively explained by some factor largely related to fatigue of the back muscles; and the same factor largely explained the variation in peak vertical load acceleration.

5.4.2 Inter-parameter Relationships of Semi-squat Posture

Canonical correlation analysis indicated that, during the repetitive manual lifting task, where the semi-squat posture was employed under freestyle conditions, dynamic floor to knuckle height leglift strength contained an extremely high amount of predictive power with relation to several kinematic and biomechanical force variables. Local muscular fatigue of the thoracic erector spinae muscles and subjective fatigue rating were also observed to possess some lesser amount of predictive power. Increases of these fatigue-indicating variables, with particular emphasis on dynamic strength, were highly associated with increases in lift duration (slower lift), peak vertical load acceleration, average force on the hands, peak extension velocity, and peak shear; and with decreases in peak lumbosacral flexion and trunk flexion at the initiation of the lift. Principal factors analysis further verified that local muscular fatigue of the thoracic erector spinae muscles and dynamic leglift floor to knuckle height strength shared some significant factor, directly related to the previously discussed kinematic and biomechanical force variables. The findings of this study, though not directly related to time or repetition, do support the findings of Kim and colleagues (1992) and Lee and colleagues (1989), who observed, during squat lifting, significant increases in load acceleration over time, with no significant increase observed in lifting speed. These findings, however, were not in agreement with those of van Dieen and colleagues (1998), who reported a decrease in lumbosacral extension velocity and an increase in lumbosacral flexion as repetitions progressed in freestyle lifting, where lifting speed was controlled.

5.4.3 Inter-parameter Relationships of Semi-stoop Posture

Results of canonical correlation analysis indicated that, where the semi-stoop posture was employed under freestyle lifting conditions, changes in dynamic floor to knuckle height leglift strength and, to some lesser extent, subjective fatigue rating and local muscular fatigue of the lumbar erector spinae muscles were very good indicators of a number of kinematic and biomechanical force parameters. Decrease in dynamic strength and increases in subjective fatigue rating and EMG median frequency of the lumbar erector spinae were observed to be very highly correlated to increased peak moment and compression forces and peak lumbosacral flexion; and highly related to increased lumbosacral flexion at the initiation of the lift and decreased lift duration (faster lift), average force on the hands, and peak vertical load acceleration. Further, where the semi-stoop posture was employed, changes in local muscular fatigue of the thoracic erector spinae muscles and, to a lesser extent subjective fatigue rating were observed to possess some amount of predictive power related to changes in the knee angle at the initiation of the lift and how hard the lower back was working. Increases in normalized median frequency of thoracic erector spinae muscles and subjective fatigue rating were associated with increases in knee angle (decreased flexion) at the initiation of the lift and normalized mean absolute value of the lumbar erector spinae muscles. These findings are consistent with the increased lumbosacral flexion and decreased knee joint angles reported by van Dieen and colleagues (1998), and Sparto and associates (1997), observed with increased repetition in a freestyle lifting task. Principal factors analysis further revealed that subjective fatigue rating and normalized EMG median frequency of the thoracic erector spinae muscles shared a common factor upon which a number of

kinematic and biomechanical force parameters loaded fairly highly (as can be observed in Table 4.38), further verifying their predictive content.

5.4.4 Inter-parameter Relationships of Stoop Posture

Where the stoop posture was employed under freestyle lifting conditions, canonical correlation analysis indicated that both dynamic floor to knuckle height leglift strength and subjective fatigue rating contained some amount of predictive strength with respect to variability in kinematic parameters. Both measures of fatigue were indicated to be excellent predictors of changes in peak lumbosacral flexion and fairly good predictors of changes in lift duration and peak vertical load acceleration. Decrease in dynamic strength or increase in subjective fatigue rating was observed to be highly associated with increased peak lumbosacral flexion, while moderately associated with decreased peak vertical acceleration and lift duration (faster lift).

Principal factors analysis revealed that the local muscular fatigue-indicating parameters of the back moderately shared a component that was highly correlated to peak lumbosacral shear force (0.93233) and extension velocity (-0.76148), average force on the hands (0.9392), and knee angle at the initiation of the lift (-0.7951). As can be observed in Table 4.40, dynamic floor to knuckle height leglift strength appeared to be comprised primarily of two factors. The first of these factors, which was loosely related to local muscular fatigue of the low back (LES), was fairly well correlated to measures of how hard the thoracic (0.43015) and lumbar (-0.87592) erector spinae, and vastii lateralis (0.82054) muscles were working and to the peak lumbosacral flexion (0.82452). The second dynamic strength factor, which was loosely related to fatigue of the upper-mid

back (TES), almost exclusively explained the variation in peak moment and compressive forces at the low back.

CHAPTER 6

SUMMARY AND CONCLUSIONS

Literature survey has revealed much evidence that suggests that the cause of lower back pain (LBP) and injury is frequently related to the posture of lifting, the load, muscle fatigue, and other factors. In repetitive lifting tasks, low back injury has often been reported resulting from loads normally well below expected tolerance levels. Studies have demonstrated, with mixed results, that as a person performs a manual lifting task expected to impose or which ultimately results in muscular fatigue, or if isolated muscle fatigue is induced otherwise, the individual's coordination and lifting strategy may tend to change, possibly changing the stresses imposed on the lower back and introducing factors which increase the risk of low back disorder. In order to provide effective ergonomic intervention and engineering controls with respect to repetitive lifting tasks, it is necessary to better understand the progressive nature and consequences of fatigue during prolonged bouts of repetitive lifting. A limited amount of research exists that deals with the progressive nature and effects of fatigue during manual repetitive lifting tasks as related to factors associated with increased risk of low back disorder. The purpose of this study was to evaluate the effect of progressive fatigue on factors, which have previously been associated with increased risk of LBP in various occupational settings, during a repetitive lifting task where freestyle lifting technique was utilized.

6.1 The Hypotheses

At the onset of this study a set of four (4) hypotheses was asserted. These hypotheses are:

1. That local muscle fatigue and general fatigue would be experienced by the subjects as the repetitive lifting task proceeded as indicated by (a) decreased EMG median frequency power, (b) decreased static strength, (c) decreased dynamic strength, and (d) increased subjective fatigue rating.

Conditionally accepted – All subjects exhibited some measure of fatigue related to the experimental task. (a) rejected - There was no significant decrease in any the mean values of EMG median frequency power across all participants for the activity of any muscle observed. While the EMG median frequency power parameters changed during the experimental task in each case, for each participant, the frequency power parameters behaved uniquely. (b) accepted - All subjects, but one, exhibited decreased static composite strength at the conclusion of the lifting task as opposed to that measured at the beginning of the task. A significant ($p=0.0184$) group mean static composite decrease (20.7%) was observed. (c) rejected – The overall mean dynamic floor to knuckle height leglift strength across the participant population did not significantly change as the task proceeded. Significant increases in dynamic strength were, however observed among participants employing a semi-squat lifting posture in their respective lifting techniques. (d) accepted – Some increase in subjective fatigue rating was observed for each participant as the experimental task proceeded. A significant ($p<0.0001$) increasing effect of time on subjective fatigue rating was observed across the participant population.

2. That the lifting strategies of the subjects would change as the repetitive lifting task proceeded, resulting in significant increases in (a) maximum EMG mean absolute value parameters, (b) duration of the lifting cycle, (c) knee angle at the initiation of

the lift, (c) lumbar vertebral (trunk) flexion angle at the initiation of the lift, (d) peak vertical load acceleration, (e) average force on the hands, (f) peak lumbar vertebral (trunk) flexion, (g) peak lumbar vertebral extension (trunk) velocity, (h) peak shear force at L5/S1 joint, (i) peak compression force at L5/S1 joint, (j) peak moment at L5/S1 joint, and (k) integrated moment at L5/S1 joint.

Rejected – None of the kinematic or force parameters observed showed a significant (at 5% α -level) increase across the participant population with respect to time. Though each parameter varied uniquely for each participant throughout the performance of the experimental task, only the participant group mean of the maximum EMG mean absolute value of the lumbar erector spinae muscle group trended ($p=0.0559$) towards a significant increase between values obtained at the initial measurement and at the final measurement during the experimental trial.

3. The onset and progression of fatigue and the variation in the kinematic and biomechanical force parameters are correlated.

Accepted – Analysis of the entire participant population data revealed moderate canonical correlations between several fatigue assessment indices (subjective fatigue rating, dynamic strength, and normalized EMG median frequency power of thoracic and lumbar erector spinae muscle groups) and a number of the kinematic and force parameters observed. Where the data were analyzed according to the lifting posture employed during the repetitive lifting task, several strong canonical correlations were observed.

4. The measured parameters of dynamically induced fatigue as measured using dynamic and static measurement techniques, as well as subjective fatigue rating are related.

Accepted – Principal factors analyses of the data of the entire participant population and of the data grouped according to the lifting posture employed during the repetitive lifting task each extracted a number of common factors yielding moderate relationships between a number of the observed parameters of fatigue.

6.2 Summary of Research and Conclusions

In order to achieve the objectives of this research, an experiment was conducted. Methodology included electromyographic amplitude and frequency parameters, subjective fatigue rating scale, static and dynamic strength measures, kinematic parameters, and measures of biomechanical force imposed on the low back and hands during a two-hour bout of repetitive lifting.

Ten male participants between the ages of 22 and 33 were selected for the experiment. The experimental lifting task consisted of each participant lifting a psychophysically determined load from floor-level to a platform 76cm in height, four times per minute for a two-hour duration, performed as eight consecutive fifteen-minute bouts. The independent variables were subject, time, and posture. Subject was a ten-level variable, one level representing each of the ten participants. The variable, time, consisted of 9 levels, accounted for time “zero” at the initiation of the experiment and each time at fifteen-minute intervals thereafter until the conclusion of the one hundred twenty-minute experimental task. As each subject was observed to perform the lifting task employing one of three discreet lifting postures, the variable, “posture,” consisted of three levels; one represented each of the three postures observed: semi-squat, semi-stoop, and stoop postures. The dependent variables were duration of the lift cycle; peak vertical load acceleration; average force on the hands; peak lumbar vertebral (trunk) flexion; peak

lumbar vertebral extension velocity; peak shear force, compression force, and moment at L5/S1 joint; integrated moment at L5/S1 joint; dynamic leglift floor to knuckle height strength; static composite strength; subjective fatigue rating; normalized median frequency and maximum amplitude of EMG of the lumbar and thoracic erector spinae and of the vastii lateralis; and knee angle and lumbar vertebral (trunk) angle at the initiation of the lift. The results of the experiment were analyzed using the multiple analysis of variance technique. Where the overall effects of independent variables or their interactions were found to be significant at the five-percent level, separate analyses of variance were utilized. Further, the experimental results were analyzed using canonical correlation and principal factors analyses. The following conclusions can be made as a result of these analyses:

1. All participants exhibited increase in some measure(s) of general physical fatigue as the two-hour lifting session proceeded. The measures of general physical fatigue generally appeared to progress, with some exception, in a unidirectional manner and were observed to be highly related to time, or repetition. This indicates that the two-hour floor to 76cm lifting task of a load of psychophysically determined maximum allowable weight, performed under freestyle lifting conditions, at a rate of four lifts per minute was sufficient to ensure some level of progressive fatigue. There was, however, no generalizable pattern of local muscular fatigue in any of the muscle groups observed, across the participant pool. Local muscular fatigue parameters were observed to vary differently between participants. Within participants, EMG median frequency parameters between muscles often appeared to exhibit inverse relationships, such that as median frequency of a muscle decreased, median

frequencies of other muscles were observed to increase. For example, cases were observed in which, within an individual, a decrease in EMG median frequency of the lumbar erector spinae across measurements was apparent, yet across the same measurements an apparent increase in EMG median frequency of the vastii lateralis was observed; thus indicating that while one muscle group was fatiguing, the other was recovering. These findings lead us to conclude that measures of local muscular fatigue alone, as have been used in previous studies, would not likely provide enough information to appropriately assess the extent of fatigue or even if fatigue was experienced during a repetitive manual lifting task, performed under freestyle lifting conditions.

2. In performance of the lifting task, participants chose different lifting strategies, utilizing discretely and quantitatively different lifting postures, which did not qualitatively change over the course of the experiment, though associated kinematic parameters were observed to vary across measurements. Further, no generalizable pattern of change in any kinematic or biomechanical force parameter was observed for all participants over time, however, substantial within subject variation for most of these parameters across measurements throughout the experimental trial was apparent. From this evidence, it is apparent that evaluation of kinematic and biomechanical force parameters simply at the beginning and at the end the of the prolonged lifting task or analysis solely of lifting posture, even where fatigue has been verified, would likely not be sufficient to provide insight into the nature of fatigue effects on a repetitive manual lifting task, performed under freestyle lifting conditions.

3. Constant variation in kinematic and biomechanical force parameters was observed within subjects throughout the experimental trial. This constant variation, viewed in conjunction with the constant changes observed in parameters indicating local muscular fatigue support the view (Sparto *et al.*, 1997) that variation in freestyle lifting parameters may, in large part, be in an effort to minimize local muscular fatigue and to limit overall fatigue. This evidence may further give support to the view (Burgess-Limerick *et al.*, 1995; Ayoub and Mital, 1989; Garg and Saxena, 1979) that, in repetitive manual lifting, the self-selected lifting technique spontaneously adopted by the participant may actually be less likely than trained, forced techniques to lead to injury, as it allows for spontaneous adjustment over time, throughout task performance, before excessive local muscular fatigue is experienced. This further supports the hypothesis that the use of restrictive equipment, such as backbelts, designed to force a particular lifting posture may contribute to increased levels of fatigue during repetitive freestyle lifting by way of restricting or preventing spontaneous adjustment during the course of the lifting task, thereby contributing to increased risk of musculoskeletal disorder and injury.
4. While we maintain that it is probable that lifting under freestyle conditions in repetitive manual lifting tasks will serve to aid in limiting fatigue and thereby present reduced risk of MSD, some level of fatigue will still be experienced and thus, its effect remains as a concern. This was the first study, to this author's knowledge, that utilized canonical correlation or principal factors analysis to examine the effects of fatigue on factors associated with repetitive manual lifting. These methods of analysis applied to the study have provided evidence that supports the view (Sparto *et*

al., 1997; Potvin, 1992; Kim *et al.*, 1992; van Dieen *et al.*, 1998) that fatigue in repetitive manual lifting under freestyle conditions may, in some cases, cause changes in lifting strategy that expose the back to increased forces and increase the risk of LBD, as opposed to those observed in an unfatigued state. Further evidence has been provided that measures of general physical, specifically dynamic lifting strength and subjective fatigue rating, and to a lesser extent, local muscular fatigue may be good predictors of such changes.

6.3 Contributions to the Literature

In an exhaustive review of the literature, no previous study was discovered that attempted to quantify levels of fatigue on a progressive continuum and determine how the biomechanical force or kinematic factors associated with the resulting lifting techniques behaved accordingly. Additionally, this was the first repetitive lifting study, to the author's knowledge, to incorporate instruments discretely measuring subjective fatigue or functional, directly task-related dynamic force production capability or strength parameters in an attempt to quantify levels of general fatigue. The study was unique from previous research because it attempted to assess the effects of fatigue on manual lifting factors in a repetitive lifting task by analyzing kinematic and biomechanical force properties of the lifting task while concurrently analyzing several indices of fatigue, such that lifting factors associated with increased risk of LBD could be assessed directly in relation to indices of fatigue. It was felt that quantification of fatigue, as a progressive "process" during manual repetitive lifting is the only way conclusions can be made about its effect on lifting factors.

Evidence was provided to support the hypothesis that there is some relationship between indicators of general fatigue and the variation in the kinematic and biomechanical force parameters in prolonged repetitive manual lifting. The data indicated that general fatigue indicator variables, namely subjective fatigue rating and dynamic floor to knuckle height leglift strength, provided a substantial amount of predictive power in relation to a number of relative kinematic and biomechanical force parameters. While the lifting strategy, technique, and associated parameters for each participant varied uniquely with respect to time throughout the performance of the experimental task, the general fatigue indicating instruments provided measures that, with some mixed results, had some power in prediction of changes in parameters associated with increased risk of LBD. Such instruments, and a better understanding of their interpretations, could be useful in identifying individuals most likely to be compromised by the performance of repetitive manual lifting tasks over a prolonged period of time.

The results of this study provide a better understanding of the progression of fatigue in manual repetitive lifting tasks utilizing the freestyle method and the effects of that “progression” on factors found to be correlated with lower back disorders. These results can be used to aid in job design in the form of development and implementation of appropriate work-rest cycles or task rotation, or in the development of employee selection tools, and may ultimately aid in a decrease in work-related low back disorders and associated costs. Further development of the instruments introduced here may also provide greater flexibility in future research as it will allow for the use of fatigue assessment alternatives which are quickly measured, easily performed, readily portable, non-invasive, and non-restrictive.

CHAPTER 7

RECOMMENDATIONS FOR FUTURE RESEARCH

The findings of this study and a thorough review of the literature lead us to make the following suggestions for future research:

1. This study has introduced two (2) measures of fatigue not previously seen in the literature used to assess fatigue during repetitive manual lifting and has shown that changes in dynamic floor to knuckle height leglift strength and subjective fatigue rating, as used here, have some predictive power with respect to changes in kinematic and low back force parameters, which may put the lifter at an increased risk for musculoskeletal injury. It is recommended that these measures of fatigue be further analyzed for appropriate interpretation and independently validated with respect to other physiological indicators of fatigue, to include VO_2 consumption, blood lactate level, and heart rate. Validation and further interpretation of these fatigue assessment tools will provide greater flexibility in future research as it will allow for the use of fatigue assessment alternatives which are quickly measured, easily performed, readily portable, non-invasive, and non-restrictive.
2. The findings of this study have demonstrated that hand and low back force parameters associated with increased risk of MSD may change with fatigue during a prolonged repetitive lifting task. While direct kinematic and force measures were analyzed in this study, greater insight into the nature of observed changes in lifting strategy and technique, to include when and how the changes

occur, may be obtained by concurrently analyzing these parameters in conjunction with measures of interjoint coordination.

3. In this study, under “freestyle lifting conditions,” it was observed that each participant tended to apply some form of one of three discreet lifting postures in his individual lifting strategy. These postures were categorized as semi-squat, semi-stoop, and stoop lifting postures. It is recommended that the same procedure with a larger participant population consisting of both males and females be performed to account for possible gender differences and differences related to lifting posture and strategy selected under “freestyle lifting conditions.”
4. It is possible that the observed relationships of kinematic and force parameters with fatigue indices may have been different under different repetitive lifting conditions such as weight, lift height (e.g. knuckle to shoulder, floor to shoulder, knee to knuckle, etc.), or lift rate. It is recommended that this possibility be considered for future study.
5. Findings of the current study are based on calculations using a two dimensional, single-arm muscle equivalent link segment model; thus, only two-dimensional parameters were observed. As increased asymmetry and increased bending and twisting moments at the low back have been previously attributed to increased fatigue in repetitive lifting tasks and have been indicated as factors associated with increased risk of LBD, it is recommended that three-dimensional modeling be used in future analysis.
6. While no participants in the current study reported any feeling of muscle soreness at the onset of the lifting task of session II, due to the three to five day period

between experimental sessions, it is possible that participants may have experienced some level of delayed-onset muscle soreness (DOMS) related to the demands of session I. As muscle soreness may have affected both the way in which individuals perceived levels of general physical fatigue and the way in which the lifting task was performed, it is recommended that the presence and possible effects of DOMS be considered for future study.

REFERENCES

- Adams, M. and Dolan, P. (1995). Recent advances in lumbar spinal mechanics and their clinical significance. *Clinical Biomechanics*, **10**, **1**, 3-19.
- Adams, M.A. and Hutton, W.C. (1981). The relevance of torsion to the mechanical derangement of the lumbar spine. *Spine*, **6**, 241-248.
- Adams, M.A. and Hutton, W.C. (1982). Prolapsed intervertebral disc: a hyperflexion injury. *Spine*, **7**, 184-191.
- Adams, M.A. and Hutton, W.C. (1985). Gradual disc prolapse. *Spine*, **10**, 524-531.
- Aghazadeh, F. (1986). Dynamic strength models for manual handling of different containers. *Journal of Human Ergology*, **15**, 131-138.
- Aghazadeh, F. and Ayoub, M.M. (1985). A comparison of dynamic- and static-strength models for prediction of lifting capacity. *Ergonomics*, **28**, **10**, 1409-1417.
- Andersson, G.B.J. (1981). Epidemiologic aspects on low back pain in industry. *Spine*, **6**, 53-60.
- Andersson, G.B.J. (1998). Epidemiology of low back pain. *Acta Orthopaedica Scandinavica*, **69**, **S281**, 28-31.
- Andersson, G.B.J., Ortengren, R., Nachemson, A. (1977). Intradiskal pressure, intra-abdominal pressure and myoelectric back muscle activity related to posture and loading. *Clinical Orthopaedics and related research*, **129**, 156-164.
- Andersson, G.B.J., Ortengren, R., Nachemson, A., Elfstrom, G. (1974). Lumbar disc pressure and myoelectric back muscle activity during sitting. *Scandinavian Journal of Rehabilitation Medicine*, **6**, 104-114.
- Andersson, G.B.J., Ortengren, R., Schultz, A. (1979). Analysis and measurement of the loads on the lumbar spine during work at a table. *Journal of Biomechanics*, **13**, 513-520.
- Astrand, P., Rodhal, K. (1977). Textbook of Work Physiology: Physiological basis of exercise, First Edition, McGraw-Hill: New York.
- Bernard, B.P., ed. (1997). Musculoskeletal disorders and workplace factors: A critical review of epidemiologic evidence for work-related musculoskeletal disorders of the neck, upper extremity, and low back. U.S. Department of Health and Human Services
- Bodguk, N. (1999). Clinical Anatomy of the Lumbar Spine and Sacrum, Third Edition, Churchill Livingstone: London.

- Brinckmann, P., Biggemann, M. and Hilweg, D. (1989). Prediction of the compressive strength of human lumbar vertebrae. *Spine*, **14**, 606-610.
- Buhr, T.A., Chaffin, D.B. and Martin, B.J. (1999). EMG Biofeedback as a tool for simulating the effects of specific leg muscle weakness on a lifting task. *Journal of Occupational Rehabilitation*, **9**, 4, 247-265.
- Burgess-Limerick, R., Abernathy, B., Neal, R.J. and Kippers, V. (1995). Self-selected manual lifting technique: Functional consequences of the interjoint coordination. *Human Factors*, **37**, 2, 395-411.
- Chaffin, D.B., Andersson, .B.J. and Martin, B.J. (1999). Occupational Biomechanics, Third Edition, Wiley-Interscience: New York.
- Chaffin, D.B. and Ashton-Miller, J.A. (1991). Biomechanical aspects of low-back pain in the older worker. *Experimental Aging Research*, **17**, 3, 177-187.
- Chaffin, D.B. and Page, G.B. (1994). Postural effects on biomechanical and psychophysical weight-lifting limits. *Ergonomics*, **37**, 4, 663-676.
- Chaffin, D.B. and Park, K.S. (1973). A longitudinal study of low-back pain as associated with occupational weight lifting factors. *American Industrial Hygiene Association Journal*, **34**, 12, 513-525.
- Cholewicki, J., McGill, S.M. and Norman, R.W. (1995). Comparison of muscle forces and joint load from an optimization and EMG assisted lumbar spine model: towards development of a hybrid approach. *Journal of Biomechanics*, **28**, 3, 321-331.
- Ciriello, V.M., Snook, S.H., Blick, A.C. and Wilkinson, P.L. (1990). The effects of task duration on psychophysically determined maximal acceptable weights and forces. *Ergonomics*, **33**, 187-200.
- Cooley, W.W., Lohnes, P.R. (1971). Multivariate Data Analysis, John Wiley & Sons, Inc: New York.
- de Leva, P. (1996). Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *Journal of Biomechanics*, **28**, 9, 1223-1230.
- De Luca, C.J. (1997). The use of surface electromyography in biomechanics (invited paper). *Journal of Applied Biomechanics*, **13**, 135-163.
- Dempster, W.T. (1955). Space requirements of the seated operator, WADC-TR-55-159, Aerospace Medical Research Laboratories: Dayton, OH.
- Dolan, P, Earley, M., Adams, M..A. (1993). Bending and compressive stresses acting on the lumbar spine during lifting activities. *Journal of Biomechanics*, **27**, 12, 1237-1248.

- Dolan, P. and Adams, M.A. (1993). Influence of lumbar hip mobility on the bending stresses acting on the lumbar spine. *Clinical Biomechanics*, **8**, 185-192.
- Dolan, P. and Adams, M.A. (2000). When do bending stresses on the spine rise to damaging levels? *Proceedings of the International Ergonomics Association 2000/Human Factors Engineering Society 2000 Congress*, **4**, 635-638.
- Dolan, P., Mannion, A.F. and Adams, M.A. (1995). Fatigue of the erector spinae muscles. A quantitative assessment using “frequency banding” of the surface electromyography signal. *Spine*, **20**, **2**, 149-159.
- Duntleman, G.H. (1989). Principal Components Analysis, Quantitative Applications in the Social Sciences Series, No. 69, Sage Publications: Thousand Oaks, California.
- Ekholm, J., Arborelius, U.P. and Nemeth, G. (1982). The load on the lumbo-sacral joint and trunk muscle activity during lifting. *Ergonomics*, **25**, **2**, 145-161.
- Everitt, B.S., Dunn, G. (1991). Applied Multivariate Data Analysis, Arnold: London.
- Fathallah, F.A., Marras, W.S. and Parniapour, M. (1998). The role of complex simultaneous trunk motions in the risk of occupationally related low back disorders. *Spine*, **23**, **9**, 1035-1042.
- Fathallah, F.A., Marras, W.S. and Parniapour, M. (2000). Combined spinal motion and loading in occupational low back disorders. *Proceedings of the International Ergonomics Association 2000/Human Factors Engineering Society 2000 Congress*, **4**, 624-626.
- Fraser, D., Potvin, J., Jones, J. (2000). Effects of trunk muscle fatigue on spine mechanics during repetitive asymmetrical lifting. *Proceedings of the International Ergonomics Association 2000/Human Factors Engineering Society 2000 Congress*, **4**, 631-634.
- Frymoyer, J.W. (1989). Epidemiology. In: Frymoyer, J.W., Gordon, S.L., eds Symposium on new perspectives on low back pain. Park Ridge, IL: American Academy of Orthopaedic Surgeons, 19-33.
- Fulco, C.S., Lewis, S.F., Frykman, P.N., Boushel, R., Smith, S., Harman, E.A., Cymerman, A. and Pandolf, K.B. (1995). Quantitation of progressive muscle fatigue during dynamic leg exercise in humans (Special Communication). *Journal of Applied Physiology*, **79**, **6**, 2154-2162.
- Garg, A. and Herrin, G.D. (1979). Stoop or squat: A biomechanical and metabolic evaluation. *American Institute of Industrial Engineers*, **11**, **4**, 894-903.

- Garg, A. and Saxena, U. (1979). Effects of lifting frequency and fatigue with special reference to psychophysical methodology and metabolic rate. *American Industrial Hygiene Association Journal*, **40**, **10**, 894-903.
- Garg A., Sharma, D., Chaffin, D.B. and Schmidler, J.M. (1983). Biomechanical stresses as related to motion trajectory of lifting. *Human Factors*, **25**, **5**, 527-539.
- Gedalia, U., Solomonow, M., Zhou, B., Barrata, V., Lu, Y. and Harris, M., (1999). Biomechanics of increased exposure to lumbar injury caused by cyclic loading: Part 2. Recovery of reflexive muscular stabilization with rest. *Spine*, **24**, **23**, 2461-2467.
- Granata, K.P., Marras, W.S. (1993). An EMG assisted model of loads on the lumbar spine during asymmetric trunk extensions. *Journal of Biomechanics*, **26**, **10**, 1429-1438.
- Gray, H. (1977). *Anatomy, Perspective and Surgical*, Revised American from Fifteenth English Edition, Gramercy Books: New Jersey.
- Hammer, W (1993). *Product Safety Management and Engineering*, American Society of Safety Engineers, 2.
- Hansson, T., Roos, B. and Nachemson, A. (1980). The bone mineral content and ultimate compressive bone strength of lumbar vertebrae. *Spine*, **5**, 16-55.
- Hart, G.L., Deyo, R.A. and Cherkin, D.C. (1995). Physician office visits for low back pain. *Spine*, **20**, 11-19.
- Hsu, J. J. S. (1987). *Investigation of Fatigue in Lifting Through Bio-Mechanical and Physiological Evaluation*, Unpublished dissertation, Louisiana State University.
- Hutton, W.C. and Adams, M.A. (1982). Can the lumbar spine be crushed in heavy lifting? *Spine*, **7**, 586-590.
- Jabre, J.F. and Hackett, E.R. (1983). *EMG Manual*, Charles C. Thomas Publishers: Springfield, IL.
- Jackson, A.S. (1999). *Physical Working Capacity and Functional Capacity Evaluation System*, Version 2.0, Lafayette Instruments: USA.
- Kansas Department of Human Resources (2000). *Workers Compensation 26th Annual Report*, Fiscal Year 2000.
- Kim, S.H. and Chung, M.K. (1995). Effects of posture, weight and frequency on trunk muscular activity and fatigue during repetitive lifting. *Ergonomics*, **38**, **5**, 853-863.

- Kim, Y., Lee, K. and Aghazadeh, F. (1992). Fatigue effect on lifting acceleration in frequent lifting. *Proceedings of the Human Factors Society 36th Annual Meeting*, 649-653.
- Kincaid, J.C. (1997). Muscle pain, fatigue, and fasciculations. *Neurologic Clinics*, **15**, 3, 697-709.
- Kroemer, K. H. E., Kroemer, H. J., Kroemer-Elbert, K. E. (1986). Engineering Physiology, Physiologic Bases of Human Factors/Ergonomics. *Advances in Human Factors/Ergonomics*, **4**, Elsevier: New York.
- Lee, K., Mital, A., Aghazadeh, F. and Hsu, J. (1989). A study of lifting characteristics of frequent lifting. In: Mital, A., ed. *Advances in Industrial Ergonomics and Safety I*, Taylor & Francis, 701-706.
- Leskinen, T.P.J., Stalhammar, H.R., Rautanen, M.T. (1992). Biomechanically and electromyographically assessed load on the spine in self-paced and force-paced lifting work. *Ergonomics*, **35**, 7/8, 881-888.
- Levine, M.S. (1977). Canonical analysis and factor comparison. Quantitative Applications in the Social Sciences Series, No. 6, Sage Publications: Thousand Oaks, California.
- Liebensohn, C.S. (1992). Pathogenesis of Chronic Back Pain. *Journal of Manipulative and Physiological Therapeutics*, **15**, 5, 299-308.
- Lindbeck, L. and Arborelius, U.P. (1991). Inertial effects from single body segments in dynamic analysis of lifting. *Ergonomics*, **34**, 4, 421-433.
- Lu, H., Aghazadeh, F. (1994). Psychophysical determination and modeling of load carrying capacity. *International Journal of Industrial Ergonomics*, **13**, 51-65.
- Mardia, K.V., Kent, J.T., Bibby, J.M. (1979). Multivariate Analysis, Academic Press: London.
- Marras, W.M., Lavender, S.A., Leurgans, S.E., Fathallah, F.A., Ferguson, S.A. and Allread, W.G. (1995). Biomechanical risk factors for occupationally-related low back disorders. *Ergonomics*, **38**, 2, 377-410.
- Marras, W.M., Lavender, S.A., Leurgans, S.E., Rajulu, S.L., Allread, W.G. and Fathallah, F.A. (1993). The role of three-dimensional trunk motion in occupationally-related low back disorders: The effects of workplace factors, trunk position, and trunk motion characteristics on risk of injury. *Spine*, **18**, 5, 617-628.
- Marras, W.S., Granata, K.P. (1996). Spine loading during trunk lateral bending motions. *Journal of Biomechanics*, **30**, 7, 697-703.

- McArdle, W. D., Katch, F. I., Katch, V. L. (1996). Exercise Physiology: Energy, Nutrition, and Human Performance, Fourth Edition, Williams & Wilkins: Baltimore.
- McGill, S.M. (1997). The biomechanics of low back injury: Implications on current practice in industry. *Journal of Biomechanics*, **30**, **5**, 465-475.
- McGill, S.M. and Norman, R.W. (1985). Effects of an anatomically detailed erector spinae model on L4/L5 disc compression and shear. *Journal of Biomechanics*, **20**, **6**, 591-600.
- McGill, S.M. and Norman, R.W. (1987). Dynamically and statically determined low back moments during lifting. *Journal of Biomechanics*, **18**, 877-885.
- McGill, S.M. and Norman, R.W. (1993). Low back biomechanics in industry: The prevention of injury through safer lifting. In *Current Issues in Biomechanics* (M.D. Grabiner ed.). Human Kinetics Publishers, Champaign, IL. 69-120.
- Mendoza, T., Wang, X.S., Cleeland, C.S., Morrissey, M., Johnson, B.A., Wendt, J.K. and Huber, S.L. (1999). The rapid assessment of fatigue severity in cancer patients: Use of the Brief Fatigue Inventory. *Cancer*, **85**, 1186-96.
- Merletti, R., Knaflitz, M. and De Luca, C.J. (1990). Myoelectric manifestations of fatigue in voluntary and electrically elicited contractions. *Journal of Applied Physiology*, **69**, **5**, 1810-1820.
- Miller, D.I. and Morrison, W.E. (1975). Prediction of segmental parameters using the Havanan human body model. *Medicine and Science in Sports*, **7**, **3**, 207-212.
- Mital, A., Aghazadeh, F. and Karwowski, W. (1986). Relative importance of isometric and isokinetic lifting strengths in estimating maximum lifting capabilities. *Journal of Safety Research*, **17**, 65-71.
- Nachemson, A., Morris, J.M. (1964). In Vivo measurements of intradiscal pressure: Discometry, a method for the determination of pressure in the lower lumbar discs. *Journal of Bone and Joint Surgery*, **46-A**, **5**, 1077-1092.
- National Academy of Sciences (2001). Musculoskeletal disorders and the workplace: low back and upper extremities. National Academy Press, Washington, D.C.
- National Institute for Occupational Safety and Health (1991), DHHS, *Work Practices Guide for Manual Lifting*.
- Norman, R., Wells, R., Neumann, P., Frank, J., Shannon, H., Kerr, M. and the Ontario Universities Back Pain Study Group (1998). A comparison of peak vs. cumulative physical work exposure risk factors for the reporting of low back pain in the automotive industry. *Clinical Biomechanics*, **13**, 561-573.

- Occupational Safety and Health Administration (1992). *OSHA Technical Manual*, TED 1-0.15A.
- Ortengren, R., Andersson, B.J.G., Nachemson, A. (1981). Studies of relationships between lumbar disc pressure, myoelectric back muscle activity, and abdominal (intra-gastric) pressure. *Spine*, **6**, 1, 98-103.
- Petrofsky, J.S. and Lind, A.R. (1978). Metabolic, cardiovascular, and respiratory factors in the development of fatigue in lifting tasks. *Journal of Applied Physiology*, **45**, 1, 64-68.
- Plagenhoef, S., Evans, F.G. and Abdelnour, T. (1983). Anatomical data for analyzing human motion. *Research Quarterly for Exercise and Sport*, **54**, 2, 169-178.
- Porterfield, J.A. and DeRosa, C. (1998). *Mechanical Low Back Pain, Perspectives in Functional Anatomy*, Second Edition, W.B. Saunders Company: Philadelphia.
- Potvin, J.R. (1992). The influences of fatigue on hypothesized mechanisms of injury to the low back during repetitive lifting, Unpublished dissertation. University of Waterloo, Ontario, Canada.
- Potvin, J.R. and Norman, R.W. (1993). Quantification of erector spinae muscle fatigue during prolonged, dynamic lifting tasks. *European Journal of Applied Physiology*, **67**, 554-562.
- Punnett, L., Fine, L.J., Keyserling, W.M., Herrin, G.D. and Chaffin, D.B. (1991). Back disorders and nonneutral trunk postures of automobile assembly workers. *Scandinavian Journal of Work, Environment, and Health*, **17**, 5, 337-346.
- Richardson, C., Jull, G., Hodges, P. and Hides, J. (1999). *Therapeutic Exercise for Spinal Segmental Stabilization in Low Back Pain, Scientific Basis and Clinical Approach*, Churchill Livingstone: London.
- Roebuck, J.A., Kroemer, K.H.E. and Thompson, W.G. (1975). *Engineering Anthropometry Methods*, Wiley-Interscience: New York.
- Roy, S.H., De Luca, C.J. and Casavant, D.A. (1988). Lumbar muscle fatigue and chronic lower back pain. *Spine*, **14**, 9, 992-1001.
- Schultz, A. B., and Andersson, G. B. J. (1981). Analysis of Loads on the Lumbar Spine **6**, 76-82,.
- Schultz, A. B., Andersson, G. B. J., Ortengren, R., Haderspeck, K., Nachemson, A. (1982). Loads on the Lumbar Spine. *The Journal of Bone and Joint Surgery*, **64A**, 5.
- Shekelle, P.G., Markovich, M. and Louie, R. (1995). An epidemiologic study of episodes of back pain care. *Spine*, **20**, 15, 1668-1673.

- Snook, H. (1988) Approaches to the Control of Back Pain in Industry: Job Design, Job Placement and Education/Training, Professional Safety Vol. 33. **8**, 23-31.
- Snook, S.H., Irvine, C.H. and Bass, S.F. (1970). Maximum Weights and Work Loads Acceptable to Male Industrial Workers. *American Industrial Hygiene Association Journal*, **31**, **12**.
- Solomonow, M., Hatipkarasulu, S., Zhou, B., Barrata, R.V., Aghazadeh, F. (in print). Biomechanics and electromyography of common idiopathic low back disorder. *Spine*.
- Solomonow, M., Zhou, B., Barrata, R.V., Lu, Y. and Harris, M. (1999). Biomechanics of increased exposure to lumbar injury caused by cyclic loading: Part 1. Loss of reflexive muscular stabilization. *Spine*, **24**, **23**, 2426-2434.
- Solomonow, M., Zhou, B., Harris, M., Lu, Y. and Barrata, V. (1998). The ligamento-muscular stabilizing system of the spine. *Spine*, **23**, **23**, 2552-2562.
- Sparto, P.J., Parnianpour, M., Reinsel, T.E. and Simon, S. (1997). The effect of fatigue on multijoint kinematics, coordination, and postural stability during a repetitive lifting test. *Journal of Orthopaedic and Sports Physical Therapy*, **25**, **1**, 3-12.
- Straker, L.M. (1994). Risk assessment in combination manual handling tasks, Unpublished dissertation. Sidney University, Sidney, Australia.
- Stubbs, M., Harris, M., Solomonow, M., Zhou, B., Lu, Y. and Barrata, V. (1998). Ligamento-muscular protective reflex in the lumbar spine of the feline. *Journal of Electromyography and Kinesiology*, **8**, 197-204.
- Tabachnick, B.G., Fidell, L.S. (1996). Using Multivariate Statistics, Third Edition, Harpercollins College Publishers: New York.
- Thompson, B. (1984). Canonical correlation analysis: Uses and interpretation, Quantitative Applications in the Social Sciences Series, No. 47, Sage Publications: Thousand Oaks, California.
- Trafimow, J.H., Schipplein, O.D., Novak, G.J. and Andersson, G.B.J. (1993). The effects of quadriceps fatigue on the technique of lifting. *Spine*, **18**, **3**, 364-367.
- van Dieen, J.H., Hoozemans, M.J.M. and Toussaint, H.M. (2000). A review of biomechanical studies on stoop and squat lifting. *Proceedings of International Ergonomics Association 2000/Human Factors and Ergonomics Society 2000 Congress*, **4**, 643-646.
- van Dieen, J.H. and Toussaint, H.M. (1996). Fatigue-related changes in the coordination of lifting and their effect on low back load. *Journal of Motor Behavior*, **28**, **4**, 304-314.

- van Dieen, J.H., van den Burg, P., Raaijmakers, T.A.J. and Toussaint, H.M. (1998). Effects of repetitive lifting on kinematics: inadequate anticipatory control or adaptive changes? *Journal of Motor Behavior*, **30**, **1**, 20-32.
- Waikar, A., Lee, K., Aghazadeh, F. and Parks, C. (1991). Evaluating lifting tasks using subjective biomechanical estimates of stress at the lower back. *Ergonomics*, **34**, **1**, 33-47.
- Webb Associates. (1978). Anthropometric Source Book, Vol I, NASA 1024, National Aeronautics and Space Administration: Washington DC.
- Winter, D.A. (1990). Biomechanics and Motor Control of Human Movement, Second Edition, John Wiley & Sons: Toronto.
- Yoshikawa, T., Mori, S., Santiesteban, A.J., Sun, T.C., Hafstad, E., Chen, J. and Burr, D.B. (1994). The effects of muscle fatigue on bone strain. *Journal of Experimental Biology*, **188**, 217-233.

APPENDIX A
CONSENT FORM

CONSENT FORM

1. Study Title: *Fatigue Effects on Manual Lifting Posture*.
2. Performance Site: Data collection will be performed in the Motor Behavior Laboratory located in the room 3 Gym-Armory, LSU, Baton Rouge.
3. Contact: The following investigators can be contacted at the Department of Industrial and Manufacturing Systems Engineering at following numbers between the hours of 8:00 am and 4:30 pm, Monday through Friday.

Dr. Fred Aghazadeh 225-388-5367 Dr. Sherif M. Waly 225-388-5364

4. Purpose of the Study: The effects of work duration and fatigue on lifting posture in repetitive manual lifting tasks will be evaluated.
5. Subject Inclusion: Ten (10) male subjects between 18 and 35 years of age will be recruited from the Louisiana State University student body. All subjects will be free from back pain and have no musculoskeletal abnormalities. Participants who answer YES to any of the following questions will be excluded from the research.

YES NO

☐	☐	1.	Has your doctor ever said you have heart trouble?
☐	☐	2.	Do you frequently have pains in your heart and chest?
☐	☐	3.	Do you often feel faint or have spells of severe dizziness?
☐	☐	4.	Has a doctor ever said your blood pressure was too high?
☐	☐	5.	Has your doctor ever told you that you have a bone or joint problem such as arthritis that has been aggravated by exercise or might be made worse with exercise?
☐	☐	6.	Is there a good physical reason not mentioned here why you should not lift light to moderate loads even if you wanted to?
☐	☐	7.	Have you ever had back pain, particularly lower back pain, or spinal/disk surgery?

6. Number of subjects: 10

7. Study Procedures: The experiment will be explained to the participants and they will be asked to read and sign the consent form and then discuss the experiment with the investigator. Any questions concerning the research will be answered.

In Session 1, subjects will be initially presented with a light load, 4.3 kg. For a 20-minute period, subjects will lift the load from floor to knuckle height using a comfortable self-selected lifting technique at a rate of 4 lifts per minute. During the 20-minute trial, subjects are encouraged to adjust the weight until a maximum weight is obtained which they think they can handle for an 8-hour work period without becoming overheated, unusually tired, and or weakened. The resulting weight will serve as the functional load for the experiment. During Session 2, the subject will perform the lifting task of the functional load using the same self-selected lifting method as performed in the 20-minute trial, for a duration of 2 hours, at a rate of 4 lifts per minute.

Measurements: Throughout the experiment, joint and segment position will be continuously tracked and recorded. During the experiment, heart rate, static composite strength, dynamic lifting strength, and subjective fatigue rating

will be recorded at 0, 15, 30, 45, 60, 75, 90, 105, and 120-minute points. At the same points of the experiment, neuromuscular activity of lower back muscles will be collected by using surface electromyography (EMG).

Data Collection: Using a digital camera system, joint and segment position data will be collected and stored into a single file for each experiment. Bipolar surface EMG data collection system will be used throughout the data collection period. The data will be stored into two separate files for each measurement interval for further analysis. Heart rate measurements will be collected using a digital electronic heart rate monitor. Static composite and dynamic lifting strength measurements will be collected using a force monitor and strain gauge load cell, and a Mini-Gym and digital dynamometer, respectively at the data collection intervals, between the 15-minute lifting bouts. The resulting measurements will be recorded and stored in a single file.

8. **Benefits:** The study does not provide direct health, monetary or mental benefits to the subjects involved. The results of the study will benefit the society as it leads to a better understanding of mechanisms related to safe design of repetitive manual lifting tasks. This will help employers in placing of workers and job design to create a safer place of work.
9. **Risks:** The potential risks of participating in the study are cardiac problems, muscle soreness and/or strain, headaches, hernia, dizziness, fatigue, and vertebrae disc damage. As with all physical exertion, there is a small possibility of heart attack and similar complications. The risk of such events is minimized by frank answers to the health-screening questionnaire, designed to exclude those persons expected to be most at risk. If this research project causes any physical injury to participants in this project, treatment is not available at Louisiana State University, nor is there any insurance carried by the University or its personnel applicable to cover any such injury. Treatment and financial compensation for such injury must be provided through the participant's own insurance program. In case of emergency, the local emergency service (911) will be contacted.
10. **Right to Refuse:** Subjects may choose not to participate or to withdraw from the study at any time without penalty or loss of any benefit to which they might otherwise be entitled.
11. **Privacy:** Results of the study may be published, but no names or identifying information will be included in the publication. Subject identity will remain confidential unless the law requires disclosure. The data will be stored in a locked cabinet or password-secured computer. The screening questionnaires of rejected subjects will be destroyed.
12. **Signatures:**

The study has been discussed with me and all my questions have been answered. I may direct additional questions regarding study specifics to the investigators. If I have questions about subjects' rights or other concerns, I can contact Charles E. Graham, Institutional Review Board, (225) 388-1492. I agree to participate in the study described above and acknowledge the investigator's obligation to provide me with a signed copy of this consent form.

Signature of Subject _____ Date _____.

APPENDIX B

SUBJECTIVE FATIGUE RATING FORM

Subjective Fatigue Rating

Please indicate the level of fatigue you are currently experiencing, using the following scale, by placing an "X" in the appropriate box.

	0 min	15 min	30 min	45 min	60 min	75 min	90 min	105 min	120 min
Not at all	☐	☐	☐	☐	☐	☐	☐	☐	☐
	0	0	0	0	0	0	0	0	0
	☐	☐	☐	☐	☐	☐	☐	☐	☐
	1	1	1	1	1	1	1	1	1
Mild fatigue	☐	☐	☐	☐	☐	☐	☐	☐	☐
	2	2	2	2	2	2	2	2	2
	☐	☐	☐	☐	☐	☐	☐	☐	☐
	3	3	3	3	3	3	3	3	3
	☐	☐	☐	☐	☐	☐	☐	☐	☐
	4	4	4	4	4	4	4	4	4
Moderate fatigue	☐	☐	☐	☐	☐	☐	☐	☐	☐
	5	5	5	5	5	5	5	5	5
	☐	☐	☐	☐	☐	☐	☐	☐	☐
	6	6	6	6	6	6	6	6	6
	☐	☐	☐	☐	☐	☐	☐	☐	☐
	7	7	7	7	7	7	7	7	7
Severe fatigue	☐	☐	☐	☐	☐	☐	☐	☐	☐
	8	8	8	8	8	8	8	8	8
	☐	☐	☐	☐	☐	☐	☐	☐	☐
	9	9	9	9	9	9	9	9	9
Unable to continue	☐	☐	☐	☐	☐	☐	☐	☐	☐
	10	10	10	10	10	10	10	10	10

Subject Number

APPENDIX C

BRIEF FATIGUE INVENTORY

Brief Fatigue Inventory

STUDY ID# _____

HOSPITAL # _____

Date: ____/____/____

Time: _____

Name _____

Last

First

Middle Initial

Throughout our lives, most of us have times when we feel very tired or fatigued.
Have you felt unusually tired or fatigued in the last week? Yes ☐ No ☐

1. Please rate your fatigue (weariness, tiredness) by circling the one number that best describes your fatigue right NOW.

0	1	2	3	4	5	6	7	8	9	10
No										As bad as
Fatigue										you can imagine

2. Please rate your fatigue (weariness, tiredness) by circling the one number that best describes your USUAL level of fatigue during past 24 hours.

0	1	2	3	4	5	6	7	8	9	10
No										As bad as
Fatigue										you can imagine

3. Please rate your fatigue (weariness, tiredness) by circling the one number that best describes your WORST level of fatigue during past 24 hours.

0	1	2	3	4	5	6	7	8	9	10
No										As bad as
Fatigue										you can imagine

4. Circle the one number that describes how, during the past 24 hours, fatigue has interfered with your:

A. General activity

0	1	2	3	4	5	6	7	8	9	10
Does not interfere										Completely Interferes

B. Mood

0	1	2	3	4	5	6	7	8	9	10
Does not interfere										Completely Interferes

C. Walking ability

0	1	2	3	4	5	6	7	8	9	10
Does not interfere										Completely Interferes

D. Normal work (includes both work outside the home and daily chores)

0	1	2	3	4	5	6	7	8	9	10
Does not interfere										Completely Interferes

E. Relations with other people

0	1	2	3	4	5	6	7	8	9	10
Does not interfere										Completely Interferes

F. Enjoyment of life

0	1	2	3	4	5	6	7	8	9	10
Does not interfere										Completely Interferes

Copyright 1997
The University of Texas M. D. Anderson Cancer Center
All rights reserved.

APPENDIX D

SIGMAPLOT 2001 KINEMATIC ANALYSIS PROGRAM

```

mass=8          'mass is the mass of the load to be lifted (kg)
weight=59.1     'weight is the mass of the participant (kg)

xtoe=mean(col(27))
ytoe=mean(col(28))
for count = 1 to 300 do
cell(27,count)=xtoe
cell(28,count)=ytoe
end for

for g=1 to 8 do

cell(((g-1)*40+33),1)=0
cell(((g-1)*40+34),1)=0
for a=2 to 300 do
cell(((g-1)*40+35),a)=(cell(((g-1)*40+31),a)-cell(((g-1)*40+31),(a-1)))
'determine initiation of lift
if cell(((g-1)*40+33),1)>=0 then
if cell(((g-1)*40+33),1)<=3 then
if cell(((g-1)*40+35),a)>1 then
cell(((g-1)*40+33),1)=(cell(((g-1)*40+33),1)+1)
cell(((g-1)*40+33),2)=cell(2,a)
cell(((g-1)*40+33),3)=cell(1,a)
end if
end if
end if
end for

for b=2 to 300 do
cell(((g-1)*40+36),b)=abs(cell(((g-1)*40+35),b))
'determine end of lift
if cell(((g-1)*40+33),2)<cell(2,b) then
if cell(((g-1)*40+34),1)>=0 then
if cell(((g-1)*40+34),1)<=5 then
if cell(((g-1)*40+36),b)<1 then
cell(((g-1)*40+34),1)=(cell(((g-1)*40+34),1)+1)
c=cell(((g-1)*40+34),1)
cell(((g-1)*40+34),2)=cell(2,b)
cell(((g-1)*40+34),3)=cell(1,b)

end if
end if
end if
end if
end for

```

```

d1=cell(((g-1)*40+33),3)
e1=cell(((g-1)*40+34),3)
for f=d1 to e1 do
cell(((g-1)*20)+401,(f-d1+1))=cell(((g-1)*40)+3,f)
cell(((g-1)*20)+402,(f-d1+1))=cell(((g-1)*40)+4,f)
cell(((g-1)*20)+403,(f-d1+1))=cell(((g-1)*40)+6,f)
cell(((g-1)*20)+404,(f-d1+1))=cell(((g-1)*40)+7,f)
cell(((g-1)*20)+405,(f-d1+1))=cell(((g-1)*40)+9,f)
cell(((g-1)*20)+406,(f-d1+1))=cell(((g-1)*40)+10,f)
cell(((g-1)*20)+407,(f-d1+1))=cell(((g-1)*40)+12,f)
cell(((g-1)*20)+408,(f-d1+1))=cell(((g-1)*40)+13,f)
cell(((g-1)*20)+409,(f-d1+1))=cell(((g-1)*40)+15,f)
cell(((g-1)*20)+410,(f-d1+1))=cell(((g-1)*40)+16,f)
cell(((g-1)*20)+411,(f-d1+1))=cell(((g-1)*40)+18,f)
cell(((g-1)*20)+412,(f-d1+1))=cell(((g-1)*40)+19,f)
cell(((g-1)*20)+413,(f-d1+1))=cell(((g-1)*40)+21,f)
cell(((g-1)*20)+414,(f-d1+1))=cell(((g-1)*40)+22,f)
cell(((g-1)*20)+415,(f-d1+1))=cell(((g-1)*40)+24,f)
cell(((g-1)*20)+416,(f-d1+1))=cell(((g-1)*40)+25,f)
cell(((g-1)*20)+417,(f-d1+1))=cell(((g-1)*40)+27,f)
cell(((g-1)*20)+418,(f-d1+1))=cell(((g-1)*40)+28,f)
cell(((g-1)*20)+419,(f-d1+1))=cell(((g-1)*40)+30,f)
cell(((g-1)*20)+420,(f-d1+1))=cell(((g-1)*40)+31,f)

end for
end for

```

'*****beginning of write and replace for algorithm

```

for trial = 0 to 7 do
d=cell(((trial)*40+33),3)
e=cell(((trial)*40+34),3)
for frame = 1 to 300 do
for point = 1 to 20 do

cell((400+point),frame)=cell((400+(20*trial)+point),frame)
end for
cell(859,frame)=0
cell(865,frame)=0
cell(853,frame)=0
cell(908,frame)=0
cell(963,frame)=0
cell(962,frame)=0
cell(961,frame)=0

```

cell(851,frame)=0

end for

'ankle angle on column 850

for k=1 to (e-d+1) do

'if cell(451,k)>0 then

cell(850,k)=(atan((cell(416,k)-cell(418,k))/((cell(415,k)-
cell(417,k)))))+(atan((cell(414,k)-cell(416,k))/((cell(415,k)-cell(413,k)))))

cell(851,k)=(atan((cell(414,k)-cell(416,k))/((cell(415,k)-
cell(413,k)))))+(atan((cell(412,k)-cell(414,k))/((cell(411,k)-cell(413,k)))))

if cell(851,k)<=0 then

cell(851,k)=180+abs((atan((cell(414,k)-cell(416,k))/((cell(415,k)-
cell(413,k)))))+(atan((cell(412,k)-cell(414,k))/((cell(411,k)-cell(409,k)))))

end if

cell(852,k)=(atan((cell(412,k)-cell(414,k))/((cell(411,k)-
cell(409,k)))))+(atan((cell(410,k)-cell(412,k))/((cell(415,k)-cell(413,k)))))

'if cell(403,k)>=cell(409,k) then

'cell(853,k)=(atan((cell(403,k)-cell(409,k))/((cell(404,k)-cell(410,k)))))

'end if

'if cell(403,k)<cell(409,k) then

'cell(853,k)=180-(atan((cell(409,k)-cell(403,k))/((cell(404,k)-cell(410,k)))))

'end if

cell(854,k)=-(atan((cell(419,k)-cell(419,k+1))/((cell(420,k+1)-cell(420,k)))))

'if cell(419,k)<=cell(419,k+1) then

cell(856,k)=sqrt((((cell(419,k)-cell(419,k+1))/(1000/60))^2)+((((cell(420,k+1)-
cell(420,k))/(1000/60))^2)))

'else if cell(819,k)>cell(819,k+1) then

'cell(856,k)=0

'end if

'end if

'****vertical load vel and acc

if k>1 then

cell(858,k)=(cell(420,k)-cell(420,k-1))/(1000/60)

cell(857,k)=((cell(856,k)-cell(856,k-1))/(1000/60))

'if cell(419,k)<=cell(419,k+1) then

cell(859,k)=(cell(858,k)-cell(858,k-1))/(1/60)

'else if cell(419,k)>cell(419,k+1) then

```

'cell(859,k)=0
'end if
'end if

****horizontal load vel and acc
cell(860,k)=(cell(419,k)-cell(419,k-1))/(1000/60)
cell(861,k)=(cell(860,k)-cell(860,k-1))/(1/60)

end if

'cell(850,k)=(atan((cell(416,k)-cell(418,k))/((cell(415,k)-
cell(417,k)))))+(atan((cell(414,k)-cell(416,k))/((cell(415,k)-cell(413,k)))))

*****lumbar vertebral for PI angle on column 853
if cell(409,k)>=cell(403,k) then
cell(853,k)=(90+atan((cell(410,k)-cell(404,k))/(cell(409,k)-cell(403,k))))
end if
if cell(403,k)>cell(409,k) then
cell(853,k)=(90-atan((cell(410,k)-cell(404,k))/(cell(409,k)-cell(403,k))))
end if
'(90+atan((cell(410,k)-cell(404,k))/(cell(409,k)-cell(403,k))))
'-atan((cell(411,k)-cell(409,k))/(cell(410,k)-cell(412,k)))
*****Hand Force on column 865
if cell(419,k)<=cell(419,k+1) then
'cell(866,k)=mass*(cell(857,k))
cell(865,k)=mass*(sqrt(((9.81+(cell(859,k))^2)+((cell(861,k))^2)))
else if cell(419,k)>cell(419,k+1) then
cell(865,k)=mass*(sqrt(((9.81-(cell(859,k))^2)+((cell(861,k))^2)))
end if
end if
*****angle of box from horizontal on column 419
'if cell(419,k)<cell(419,k+1) then
'if cell(420,k+1)<cell(420,k) then
'cell(854,k)=(atan((cell(420,k)-cell(420,k+1))/((cell(419,k+1)-cell(419,k)))))
'end if
'end if
'if cell(419,k)>=cell(419,k+1) then
'if cell(420,k+1)<cell(420,k) then
'cell(854,k)=(atan((cell(420,k)-cell(420,k+1))/((cell(419,k)-cell(419,k+1)))))
'end if
'end if
'if cell(419,k)>=cell(419,k+1) then

```

```

'if cell(420,k+1)>=cell(420,k) then
'cell(854,k)=(atan((cell(420,k+1)-cell(420,k))/((cell(419,k)-cell(419,k+1)))))
'end if
'end if
'if cell(419,k)<cell(419,k+1) then
'if cell(420,k+1)>=cell(420,k) then
'cell(854,k)=(atan((cell(420,k+1)-cell(420,k))/((cell(419,k+1)-cell(419,k)))))
'end if
'end if
'if cell(419,k)=cell(419,k+1) then
'cell(854,k)=90
'end if
'if cell(420,k)=cell(420,k+1) then
'cell(854,k)=0
'end if

```

*****wrist angle on column 900

```

if cell(419,k)>=cell(407,k) then
cell(900,k)=(atan((cell(408,k)-cell(420,k))/((cell(419,k)-cell(407,k)))))
end if
if cell(419,k)<cell(407,k) then
cell(900,k)=(atan((cell(408,k)-cell(420,k))/((cell(407,k)-cell(419,k)))))
end if

```

*****angle of elbow from horizontal on column 901

```

if cell(406,k)>=cell(408,k) then
if cell(407,k)>=cell(405,k) then
cell(901,k)=(atan((cell(406,k)-cell(408,k))/((cell(407,k)-cell(405,k)))))
end if
end if
if cell(406,k)<cell(408,k) then
if cell(407,k)>=cell(405,k) then
cell(901,k)=(atan((cell(408,k)-cell(406,k))/((cell(407,k)-cell(405,k)))))
end if
end if
if cell(406,k)>=cell(408,k) then
if cell(407,k)<cell(405,k) then
cell(901,k)=180-(atan((cell(406,k)-cell(408,k))/((cell(405,k)-cell(407,k)))))
end if
end if
if cell(901,k)>90 then
cell(901,k)=(180-cell(901,k))
end if

```


****shoulder angle on column 902

```
if cell(401,k)>=cell(405,k) then
cell(902,k)=(atan((cell(402,k)-cell(406,k))/((cell(401,k)-cell(405,k)))))
end if
if cell(401,k)<cell(405,k) then
cell(902,k)=(atan((cell(402,k)-cell(406,k))/((cell(405,k)-cell(401,k)))))
end if
if cell(902,k)>90 then
cell(902,k)=(180-cell(902,k))
end if
```

****15/s1 angle on column 903

```
if cell(410,k)>=cell(402,k) then
cell(903,k)=(atan((cell(410,k)-cell(402,k))/((cell(409,k)-cell(401,k)))))
end if
if cell(410,k)<cell(402,k) then
cell(903,k)=(atan((cell(402,k)-cell(410,k))/((cell(409,k)-cell(401,k)))))
end if
if cell(903,k)>90 then
cell(903,k)=(180-cell(903,k))
end if
```

*****variables for moment calculations

```
forearm=.016983*weight
uparm=.027999*weight
shoulder=.366*weight
HN=.084*weight
FAcom=(.43)*(sqrt((((cell(405,k)-cell(407,k))/1000)^2)+((cell(406,k)-
cell(408,k))/1000)^2))
UAcom=(.44)*(sqrt((((cell(405,k)-cell(401,k))/1000)^2)+((cell(406,k)-
cell(402,k))/1000)^2))
HNTcom=(.63)*(sqrt((((cell(401,k)-cell(409,k))/1000)^2)+((cell(402,k)-
cell(410,k))/1000)^2))
FArog=(.53)*(sqrt((((cell(405,k)-cell(407,k))/1000)^2)+((cell(406,k)-
cell(408,k))/1000)^2))
UARog=(.54)*(sqrt((((cell(405,k)-cell(401,k))/1000)^2)+((cell(406,k)-
cell(402,k))/1000)^2))
HNTrog=(.81)*(sqrt((((cell(401,k)-cell(409,k))/1000)^2)+((cell(402,k)-
cell(410,k))/1000)^2))
```

*****COM and velocities and accelerations on columns 890-892 and 893-895 and 896-898

```
cell(890,k)=FAcom  
cell(891,k)=UAcom  
cell(892,k)=HNTcom  
cell(990,k)=FArog  
cell(991,k)=UARog  
cell(992,k)=HNTrog
```

```
if k>1 then  
cell(893,k)=(cell(890,k)-cell(890,k-1))/(1/60)  
cell(894,k)=(cell(891,k)-cell(891,k-1))/(1/60)  
cell(895,k)=(cell(892,k)-cell(892,k-1))/(1/60)  
cell(896,k)=(cell(893,k)-cell(893,k-1))/(1/60)  
cell(897,k)=(cell(894,k)-cell(894,k-1))/(1/60)  
cell(898,k)=(cell(895,k)-cell(895,k-1))/(1/60)  
end if
```

*****x-y COM and velocities and accelerations on columns 915-920, 921-926, and 927-932

```
'FOREARM  
if cell(405,k)>=cell(407,k) then  
cell(915,k)=cell(405,k)-((cos(cell(901,k)))*FAcom*1000)  
end if  
if cell(405,k)<cell(407,k) then  
cell(915,k)=cell(405,k)+((cos(cell(901,k)))*FAcom*1000)  
end if  
if cell(406,k)>=cell(408,k) then  
cell(916,k)=cell(406,k)-((sin(cell(901,k)))*FAcom*1000)  
end if  
if cell(406,k)<cell(408,k) then  
cell(916,k)=cell(406,k)+((sin(cell(901,k)))*FAcom*1000)  
end if
```

```
'UPPER ARM  
if cell(401,k)>=cell(405,k) then  
cell(917,k)=cell(405,k)-((cos(cell(902,k)))*UAcom*1000)  
end if  
if cell(401,k)<cell(405,k) then  
cell(917,k)=cell(405,k)+((cos(cell(902,k)))*UAcom*1000)  
end if  
cell(918,k)=cell(402,k)-((sin(cell(902,k)))*UAcom*1000)
```

'HEAD NECK TRUNK

cell(919,k)=cell(409,k)+((cos(cell(903,k)))*HNTcom*1000)

if cell(410,k)>=cell(402,k) then

cell(920,k)=cell(410,k)-((sin(cell(903,k)))*HNTcom*1000)

end if

if cell(410,k)<cell(402,k) then

cell(920,k)=cell(410,k)+((sin(cell(903,k)))*HNTcom*1000)

end if

'VELOCITIES and ACCELERATIONS

if k>1 then

cell(921,k)=(cell(915,k)-cell(915,k-1))/(1000/60)

cell(922,k)=(cell(916,k)-cell(916,k-1))/(1000/60)

cell(923,k)=(cell(917,k)-cell(917,k-1))/(1000/60)

cell(924,k)=(cell(918,k)-cell(918,k-1))/(1000/60)

cell(925,k)=(cell(919,k)-cell(919,k-1))/(1000/60)

cell(926,k)=(cell(920,k)-cell(920,k-1))/(1000/60)

cell(927,k)=(cell(921,k)-cell(921,k-1))/(1/60)

cell(928,k)=(cell(922,k)-cell(922,k-1))/(1/60)

cell(929,k)=(cell(923,k)-cell(923,k-1))/(1/60)

cell(930,k)=(cell(924,k)-cell(924,k-1))/(1/60)

cell(931,k)=(cell(925,k)-cell(925,k-1))/(1/60)

cell(932,k)=(cell(926,k)-cell(926,k-1))/(1/60)

end if

'*****Force from hand and box

if cell(420,k)<=cell(420,k+1) then

cell(865,k)=(mass+(.006018*weight))*(sqrt(((9.81+(cell(859,k)))^2)+((cell(861,k))^2)))

else if cell(420,k)>cell(420,k+1) then

cell(865,k)=(mass+(.006018*weight))*(sqrt(((9.81-(cell(859,k)))^2)+((cell(861,k))^2)))

end if

end if

end for

cell(855,1)=(-1*cell(853,3)+4*cell(853,2)-3*cell(853,1))/(2/60)

cell(855,2)=(-1*cell(853,4)+4*cell(853,3)-3*cell(853,2))/(2/60)

cell(855,(e-d))=(3*cell(853,(e-d))-4*cell(853,(e-d-1))+1*cell(853,(e-d-2)))/(2/60)

cell(855,(e-d+1))=(3*cell(853,(e-d+1))-4*cell(853,(e-d))+1*cell(853,(e-d-1)))/(2/60)

```

*****angular velocities and accelerations on columns 905-908 and 910-913
cell(905,1)=(-1*cell(900,3)+4*cell(900,2)-3*cell(900,1))/(2/60)
cell(905,2)=(-1*cell(900,4)+4*cell(900,3)-3*cell(900,2))/(2/60)
cell(905,(e-d))=(3*cell(900,(e-d))-4*cell(900,(e-d-1))+1*cell(900,(e-d-2)))/(2/60)
cell(905,(e-d+1))=(3*cell(900,(e-d+1))-4*cell(900,(e-d))+1*cell(900,(e-d-1)))/(2/60)

cell(906,1)=(-1*cell(901,3)+4*cell(901,2)-3*cell(901,1))/(2/60)
cell(906,2)=(-1*cell(901,4)+4*cell(901,3)-3*cell(901,2))/(2/60)
cell(906,(e-d))=(3*cell(901,(e-d))-4*cell(901,(e-d-1))+1*cell(901,(e-d-2)))/(2/60)
cell(906,(e-d+1))=(3*cell(901,(e-d+1))-4*cell(901,(e-d))+1*cell(901,(e-d-1)))/(2/60)

cell(907,1)=(-1*cell(902,3)+4*cell(902,2)-3*cell(902,1))/(2/60)
cell(907,2)=(-1*cell(902,4)+4*cell(902,3)-3*cell(902,2))/(2/60)
cell(907,(e-d))=(3*cell(902,(e-d))-4*cell(902,(e-d-1))+1*cell(902,(e-d-2)))/(2/60)
cell(907,(e-d+1))=(3*cell(902,(e-d+1))-4*cell(902,(e-d))+1*cell(902,(e-d-1)))/(2/60)

cell(908,1)=(-1*cell(903,3)+4*cell(903,2)-3*cell(903,1))/(2/60)
cell(908,2)=(-1*cell(903,4)+4*cell(903,3)-3*cell(903,2))/(2/60)
cell(908,(e-d))=(3*cell(903,(e-d))-4*cell(903,(e-d-1))+1*cell(903,(e-d-2)))/(2/60)
cell(908,(e-d+1))=(3*cell(903,(e-d+1))-4*cell(903,(e-d))+1*cell(903,(e-d-1)))/(2/60)

cell(975,1)=(-1*cell(853,3)+4*cell(853,2)-3*cell(853,1))/(2/60)
cell(975,2)=(-1*cell(853,4)+4*cell(853,3)-3*cell(853,2))/(2/60)
cell(975,(e-d))=(3*cell(853,(e-d))-4*cell(853,(e-d-1))+1*cell(853,(e-d-2)))/(2/60)
cell(975,(e-d+1))=(3*cell(853,(e-d+1))-4*cell(853,(e-d))+1*cell(853,(e-d-1)))/(2/60)

for l=3 to (e-d-1) do
cell(855,l)=(1*cell(853,l+2)+8*cell(853,l+1)-8*cell(853,l-1)-1*cell(853,l-2))/(12/60)
cell(905,l)=(1*cell(900,l+2)+8*cell(900,l+1)-8*cell(900,l-1)-1*cell(900,l-2))/(12/60)
cell(906,l)=(1*cell(901,l+2)+8*cell(901,l+1)-8*cell(901,l-1)-1*cell(901,l-2))/(12/60)
cell(907,l)=(1*cell(902,l+2)+8*cell(902,l+1)-8*cell(902,l-1)-1*cell(902,l-2))/(12/60)
cell(908,l)=(1*cell(903,l+2)+8*cell(903,l+1)-8*cell(903,l-1)-1*cell(903,l-2))/(12/60)
cell(975,l)=(1*cell(853,l+2)+8*cell(853,l+1)-8*cell(853,l-1)-1*cell(853,l-2))/(12/60)

end for

cell(910,1)=(-1*cell(905,3)+4*cell(905,2)-3*cell(905,1))/(2/60)
cell(910,2)=(-1*cell(905,4)+4*cell(905,3)-3*cell(905,2))/(2/60)
cell(910,(e-d))=(3*cell(905,(e-d))-4*cell(905,(e-d-1))+1*cell(905,(e-d-2)))/(2/60)
cell(910,(e-d+1))=(3*cell(905,(e-d+1))-4*cell(905,(e-d))+1*cell(905,(e-d-1)))/(2/60)

cell(911,1)=(-1*cell(906,3)+4*cell(906,2)-3*cell(906,1))/(2/60)

```

```

cell(911,2)=(-1*cell(906,4)+4*cell(906,3)-3*cell(906,2))/(2/60)
cell(911,(e-d))=(3*cell(906,(e-d))-4*cell(906,(e-d-1))+1*cell(906,(e-d-2)))/(2/60)
cell(911,(e-d+1))=(3*cell(906,(e-d+1))-4*cell(906,(e-d))+1*cell(906,(e-d-1)))/(2/60)

```

```

cell(912,1)=(-1*cell(907,3)+4*cell(907,2)-3*cell(907,1))/(2/60)
cell(912,2)=(-1*cell(907,4)+4*cell(907,3)-3*cell(907,2))/(2/60)
cell(912,(e-d))=(3*cell(907,(e-d))-4*cell(907,(e-d-1))+1*cell(907,(e-d-2)))/(2/60)
cell(912,(e-d+1))=(3*cell(907,(e-d+1))-4*cell(907,(e-d))+1*cell(907,(e-d-1)))/(2/60)

```

```

cell(913,1)=(-1*cell(908,3)+4*cell(908,2)-3*cell(908,1))/(2/60)
cell(913,2)=(-1*cell(908,4)+4*cell(908,3)-3*cell(908,2))/(2/60)
cell(913,(e-d))=(3*cell(908,(e-d))-4*cell(908,(e-d-1))+1*cell(908,(e-d-2)))/(2/60)
cell(913,(e-d+1))=(3*cell(908,(e-d+1))-4*cell(908,(e-d))+1*cell(908,(e-d-1)))/(2/60)

```

```

for m=3 to (e-d-1) do
cell(910,m)=(1*cell(905,m+2)+8*cell(905,m+1)-8*cell(905,m-1)-1*cell(905,m-2))/(12/60)
cell(911,m)=(1*cell(906,m+2)+8*cell(906,m+1)-8*cell(906,m-1)-1*cell(906,m-2))/(12/60)
cell(912,m)=(1*cell(907,m+2)+8*cell(907,m+1)-8*cell(907,m-1)-1*cell(907,m-2))/(12/60)
cell(913,m)=(1*cell(908,m+2)+8*cell(908,m+1)-8*cell(908,m-1)-1*cell(908,m-2))/(12/60)
end for

```

end for

*****x-y REACTION FORCES and MOMENTS

```

for z=1 to (e-d+1) do
WRIST=(sqrt((((cell(419,z)-cell(407,z))/1000)^2)+((cell(420,z)-cell(408,z))/1000)^2))
FA=(sqrt((((cell(405,z)-cell(407,z))/1000)^2)+((cell(406,z)-cell(408,z))/1000)^2))
UA=(sqrt((((cell(405,z)-cell(401,z))/1000)^2)+((cell(406,z)-cell(402,z))/1000)^2))
HNT=(sqrt((((cell(401,z)-cell(409,z))/1000)^2)+((cell(402,z)-cell(410,z))/1000)^2))
hand=cell(865,z)
axFA=cell(927,z)
ayFA=cell(928,z)
axUA=cell(929,z)
ayUA=cell(930,z)
axHNT=cell(931,z)
ayHNT=cell(932,z)

```

'WRIST

```

cell(951,z)=((mass+(.006018*weight))*(cell(859,z)))+((mass+(.006018*weight))*(9.81))
cell(950,z)=((mass+(.006018*weight))*(cell(861,z)))

```

cell(952,z)=((WRIST)*(cos(cell(900,z)))*(9.81)*(mass+(.006018*weight)))+((WRIST)*(cos(cell(900,z)))*(cell(859,z))*(mass+(.006018*weight)))-
((WRIST)*(sin(cell(900,z)))*(cell(861,z))*(mass+(.006018*weight)))

'ELBOW

cell(953,z)=(forearm*axFA)+cell(950,z)
cell(954,z)=(forearm*9.81)+(forearm*ayFA)+cell(951,z)
ME1=(((cell(890,z))*(cos(cell(901,z)))*(forearm)*(9.81)))
ME2=(((cell(890,z))*(cos(cell(901,z)))*(forearm)*(ayFA)))
ME3=(((cell(890,z))*(sin(cell(901,z)))*(forearm)*(axFA)))
ME4=((FA)*(cos(cell(901,z)))*(cell(951,z)))
ME5=((FA)*(sin(cell(901,z)))*(cell(951,z)))
ME6=((cell(990,z)-cell(890,z))*(forearm)*(cell(911,z)))
cell(955,z)=cell(952,z)+ME1+ME2-ME3+ME4-ME5+ME6

'SHOULDER

cell(956,z)=(uparm*axUA)+cell(953,z)
cell(957,z)=(uparm*9.81)+(uparm*ayUA)+cell(954,z)
MS1=(((cell(891,z))*(cos(cell(902,z)))*(uparm)*(9.81)))
MS2=(((cell(891,z))*(cos(cell(902,z)))*(uparm)*(ayUA)))
MS3=(((cell(891,z))*(sin(cell(902,z)))*(uparm)*(axUA)))
MS4=((UA)*(cos(cell(902,z)))*(cell(954,z)))
MS5=((UA)*(sin(cell(902,z)))*(cell(954,z)))
MS6=((cell(991,z)-cell(891,z))*(uparm)*(cell(912,z)))
cell(958,z)=cell(955,z)+MS1+MS2-MS3+MS4-MS5+MS6

'L5

cell(959,z)=(HN*axHNT)+cell(956,z)
cell(960,z)=(HN*9.81)+(HN*ayHNT)+cell(957,z)
ML1=(((cell(892,z))*(cos(cell(903,z)))*(HN)*(9.81)))
ML2=(((cell(892,z))*(cos(cell(903,z)))*(HN)*(ayHNT)))
ML3=(((cell(892,z))*(sin(cell(903,z)))*(HN)*(axHNT)))
ML4=((HNT)*(cos(cell(903,z)))*(cell(957,z)))
ML5=((HNT)*(sin(cell(903,z)))*(cell(957,z)))
ML6=((cell(992,z)-cell(892,z))*(HN)*(cell(913,z)))
cell(961,z)=cell(958,z)+ML1+ML2-ML3+ML4-ML5+ML6

'COMPRESSION FORCE

cell(962,z)=((cell(961,z))/0.075)+(((cos(cell(903,z)))*(cell(959,z))))+(((sin(cell(903,z)))*(cell(960,z))))

'SHEAR FORCE

cell(963,z)=((cell(959,z))*(sin(cell(903,z))))+((cos(cell(903,z)))*(cell(960,z)))

'TRUNK EXTENSION VELOCITY (linear)

'cell(975,z)=(sqrt(((cell(925,z))^2)+((cell(926,z))^2)))

```

*****clear original frames
end for
for yo=1 to 20 do
for yoyo=1 to 300 do
cell((400+yo),yoyo)=0
end for
end for
*****

cell((1000+trial+2),2)=max(col(859))
cell((1000+trial+2),3)=(total(col(865)))/(e-d+1)
cell((1000+trial+2),4)=max(col(853))
cell((1000+trial+2),5)=max(col(908))
cell((1000+trial+2),6)=max(col(963))
cell((1000+trial+2),7)=max(col(962))
cell((1000+trial+2),8)=max(col(961))
cell((1000+trial+2),9)=(total(col(961)))
cell((1000+trial+2),16)=cell(853,1)
cell((1000+trial+2),17)=cell(851,1)
cell((1000+trial+2),18)=(e-d+1)/60

for u =1 to (e-d+1) do
if cell(859,u)=cell((1000+trial+2),2) then
cell((1000+trial+2),10)=int((u/(e-d+1))*100)
end if

if cell(853,u)=cell((1000+trial+2),4) then
cell((1000+trial+2),11)=int((u/(e-d+1))*100)
end if

if cell(908,u)=cell((1000+trial+2),5) then
cell((1000+trial+2),12)=int((u/(e-d+1))*100)
end if

if cell(963,u)=cell((1000+trial+2),6) then
cell((1000+trial+2),13)=int((u/(e-d+1))*100)
end if

if cell(962,u)=cell((1000+trial+2),7) then
cell((1000+trial+2),14)=int((u/(e-d+1))*100)
end if

if cell(961,u)=cell((1000+trial+2),8) then
cell((1000+trial+2),15)=int((u/(e-d+1))*100)
end if

```

end for
end for

cell(1000,1)="Postural Index"
cell(1000,2)="Peak vert acc"
cell(1000,3)="Average Hand Force"
cell(1000,4)="Peak Trunk Flexion"
cell(1000,5)="Peak Ext Vel"
cell(1000,6)="Peak Shear"
cell(1000,7)="Peak Compr"
cell(1000,8)="Peak Moment"
cell(1000,9)="Int Moment"
cell(1000,10)="% at Peak vert acc"
cell(1000,11)="% at Peak Trunk Flexion"
cell(1000,12)="% at Peak Ext Vel"
cell(1000,13)="% at Peak Shear"
cell(1000,14)="% at Peak Compr"
cell(1000,15)="% at Peak Moment"
cell(1000,16)="Flx"
cell(1000,17)="Knee"
cell(1000,18)="Lift Time"

cell(1001,2)=mean({(cell(1002,2)), (cell(1003,2)), (cell(1004,2)), (cell(1005,2)),
(cell(1006,2)), (cell(1007,2)), (cell(1008,2)), (cell(1009,2))})
cell(1001,3)=mean({(cell(1002,3)), (cell(1003,3)), (cell(1004,3)), (cell(1005,3)),
(cell(1006,3)), (cell(1007,3)), (cell(1008,3)), (cell(1009,3))})
cell(1001,4)=mean({(cell(1002,4)), (cell(1003,4)), (cell(1004,4)), (cell(1005,4)),
(cell(1006,4)), (cell(1007,4)), (cell(1008,4)), (cell(1009,4))})
cell(1001,5)=mean({(cell(1002,5)), (cell(1003,5)), (cell(1004,5)), (cell(1005,5)),
(cell(1006,5)), (cell(1007,5)), (cell(1008,5)), (cell(1009,5))})
cell(1001,6)=mean({(cell(1002,6)), (cell(1003,6)), (cell(1004,6)), (cell(1005,6)),
(cell(1006,6)), (cell(1007,6)), (cell(1008,6)), (cell(1009,6))})
cell(1001,7)=mean({(cell(1002,7)), (cell(1003,7)), (cell(1004,7)), (cell(1005,5)),
(cell(1006,7)), (cell(1007,7)), (cell(1008,7)), (cell(1009,7))})
cell(1001,8)=mean({(cell(1002,8)), (cell(1003,8)), (cell(1004,8)), (cell(1005,8)),
(cell(1006,8)), (cell(1007,8)), (cell(1008,8)), (cell(1009,8))})
cell(1001,9)=mean({(cell(1002,9)), (cell(1003,9)), (cell(1004,9)), (cell(1005,9)),
(cell(1006,9)), (cell(1007,9)), (cell(1008,9)), (cell(1009,9))})
cell(1001,10)=mean({(cell(1002,10)), (cell(1003,10)), (cell(1004,10)), (cell(1005,10)),
(cell(1006,10)), (cell(1007,10)), (cell(1008,10)), (cell(1009,10))})
cell(1001,11)=mean({(cell(1002,11)), (cell(1003,11)), (cell(1004,11)), (cell(1005,11)),
(cell(1006,11)), (cell(1007,11)), (cell(1008,11)), (cell(1009,11))})
cell(1001,12)=mean({(cell(1002,12)), (cell(1003,12)), (cell(1004,12)), (cell(1005,12)),
(cell(1006,12)), (cell(1007,12)), (cell(1008,12)), (cell(1009,12))})


```

cell(1001,13)=mean( {(cell(1002,13)), (cell(1003,13)), (cell(1004,13)), (cell(1005,13)),
(cell(1006,13)), (cell(1007,13)), (cell(1008,13)), (cell(1009,13))})
cell(1001,14)=mean( {(cell(1002,14)), (cell(1003,14)), (cell(1004,14)), (cell(1005,14)),
(cell(1006,14)), (cell(1007,14)), (cell(1008,14)), (cell(1009,14))})
cell(1001,15)=mean( {(cell(1002,15)), (cell(1003,15)), (cell(1004,15)), (cell(1005,15)),
(cell(1006,15)), (cell(1007,15)), (cell(1008,15)), (cell(1009,15))})
cell(1001,16)=mean( {(cell(1002,16)), (cell(1003,16)), (cell(1004,16)), (cell(1005,16)),
(cell(1006,16)), (cell(1007,16)), (cell(1008,16)), (cell(1009,16))})
cell(1001,17)=mean( {(cell(1002,17)), (cell(1003,17)), (cell(1004,17)), (cell(1005,17)),
(cell(1006,17)), (cell(1007,17)), (cell(1008,17)), (cell(1009,17))})
cell(1001,18)=mean( {(cell(1002,18)), (cell(1003,18)), (cell(1004,18)), (cell(1005,18)),
(cell(1006,18)), (cell(1007,18)), (cell(1008,18)), (cell(1009,18))})

```

APPENDIX E

SIGMAPLOT 2001 EMG ANALYSIS PROGRAM

```
width = 250
GAIN1 = 400
GAIN2 = 8000
GAIN3 = 8000
GAIN4 = 8000
GAIN5 = 8000
GAIN6 = 8000
```

```
'Time on Column 1
'one EMG on Col  2
'one EMG on Col  3
'one EMG on Col  4
'one EMG on Col  5
'one EMG on Col  6
'one EMG on Col  7
```

```
'MAV  output  on col 12, 13, 14, 15, 16, 17
```

```
'Take DC-Offset off
col(2) = col(2)-mean(col(2))
col(3) = col(3) - mean(col(3))
col(4) = col(4)-mean(col(4))
col(5) = col(5) - mean(col(5))
col(6) = col(6)-mean(col(6))
col(7) = col(7) - mean(col(7))
```

```
'Replace with Adjusted Raw EMG
col(2) = col(2)/GAIN1
col(3) = col(3)/GAIN2
col(4) = col(4)/GAIN3
col(5) = col(5)/GAIN4
col(6) = col(6)/GAIN5
col(7) = col(7)/GAIN6
```

```
'Mean Absolute Value Calculation
```

```
cell(18,1)  =  0
cell(18,2)  =  0
cell(18,3)  =  0
cell(18,4)  =  0
cell(18,5)  =  0
cell(18,6)  =  0
```

```

for i = 1 to 2*width do
cell(18,1) = cell(18,1)+abs(cell(2,i))
cell(18,2) = cell(18,2)+abs(cell(3,i))
cell(18,3) = cell(18,3)+abs(cell(4,i))
cell(18,4) = cell(18,4)+abs(cell(5,i))
cell(18,5) = cell(18,5)+abs(cell(6,i))
cell(18,6) = cell(18,6)+abs(cell(7,i))
end for

cell(18,1) = cell(18,1)/(2*width)
cell(18,2) = cell(18,2)/(2*width)
cell(18,3) = cell(18,3)/(2*width)
cell(18,4) = cell(18,4)/(2*width)
cell(18,5) = cell(18,5)/(2*width)
cell(18,6) = cell(18,6)/(2*width)

for j = 1+ width to size(col(2))-width do
cell(18,1) = cell(18,1) + (abs(cell(2,j+width))-abs(cell(2,j-width)))/(2*width+1)
cell(12,j) = cell(18,1)
cell(18,2) = cell(18,2) + (abs(cell(3,j+width))-abs(cell(3,j-width)))/(2*width+1)
cell(13,j) = cell(18,2)
cell(18,3) = cell(18,3) + (abs(cell(4,j+width))-abs(cell(4,j-width)))/(2*width+1)
cell(14,j) = cell(18,3)
cell(18,4) = cell(18,4) + (abs(cell(5,j+width))-abs(cell(5,j-width)))/(2*width+1)
cell(15,j) = cell(18,4)
cell(18,5) = cell(18,5) + (abs(cell(6,j+width))-abs(cell(6,j-width)))/(2*width+1)
cell(16,j) = cell(18,5)
cell(18,6) = cell(18,6) + (abs(cell(7,j+width))-abs(cell(7,j-width)))/(2*width+1)
cell(17,j) = cell(18,6)
end for

for k = 2 to width do
cell(12,k) = cell(12,k-1)+abs(cell(12,k))/k
cell(13,k) = cell(13,k-1)+abs(cell(13,k))/k
cell(14,k) = cell(14,k-1)+abs(cell(14,k))/k
cell(15,k) = cell(15,k-1)+abs(cell(15,k))/k
cell(16,k) = cell(16,k-1)+abs(cell(16,k))/k
cell(17,k) = cell(17,k-1)+abs(cell(17,k))/k
end for

cell(10,1)="*****"
cell(11,1)="MAX MAV"
cell(10,2)="TESL"
cell(10,3)="TESR"
cell(10,4)="LESL"
cell(10,5)="LESR"

```

```

cell(10,6)="VLL"
cell(10,7)="VLR"
cell(11,2)=max(col(12))
cell(11,3)=max(col(13))
cell(11,4)=max(col(14))
cell(11,5)=max(col(15))
cell(11,6)=max(col(16))
cell(11,7)=max(col(17))

```

```

cell(121,1)=0
cell(122,1)=0
for a=2 to 300 do
cell(120,a)=(cell(110,a)-cell(110,(a-1)))

```

```

'determine initiation of lift
if cell(121,1)>=0 then
if cell(121,1)<=3 then
if cell(120,a)>1 then
cell(121,1)=(cell(121,1)+1)
cell(121,2)=cell(81,a)
cell(121,3)=cell(80,a)
end if
end if
end if
end for

```

```

for b=2 to 300 do
cell(123,b)=abs(cell(110,b)-cell(110,(b-1)))

```

```

'determine end of lift
if cell(121,2)<cell(81,b) then
if cell(122,1)>=0 then
if cell(122,1)<=5 then
if cell(123,b)<1 then
cell(122,1)=(cell(122,1)+1)
c=cell(122,1)
cell(122,2)=cell(81,b)
cell(122,3)=cell(80,b)
cell(124,c)=cell(81,b)
end if
end if
end if
end if

```

```

end for

```

```

'Fast Fourier Transformation
e=cell(121,3)
for m = 0 to 4 do
for n = 1 to 256 do
cell(32,n) = cell(2,e+n+(m*256))
cell(33,n) = cell(3,e+n+(m*256))
cell(34,n) = cell(4,e+n+(m*256))
cell(35,n) = cell(5,e+n+(m*256))
cell(36,n) = cell(6,e+n+(m*256))
cell(37,n) = cell(7,e+n+(m*256))
end for
col(42) = abs(fft(col(32)))
col(43) = abs(fft(col(33)))
col(44) = abs(fft(col(34)))
col(45) = abs(fft(col(35)))
col(46) = abs(fft(col(36)))
col(47) = abs(fft(col(37)))
for p = 1 to 128 do
cell(21,p+(m*256)) = p
cell(22,p+(m*256)) = cell(42,p)
cell(23,p+(m*256)) = cell(43,p)
cell(24,p+(m*256)) = cell(44,p)
cell(25,p+(m*256)) = cell(45,p)
cell(26,p+(m*256)) = cell(46,p)
cell(27,p+(m*256)) = cell(47,p)
end for

```

'CALCULATE MEDIAN FREQUENCY

```

cell(52,1+(m*256))=cell(22,1+(m*256))*cell(21,1+(m*256))
cell(53,1+(m*256))=cell(23,1+(m*256))*cell(21,1+(m*256))
cell(54,1+(m*256))=cell(24,1+(m*256))*cell(21,1+(m*256))
cell(55,1+(m*256))=cell(25,1+(m*256))*cell(21,1+(m*256))
cell(56,1+(m*256))=cell(26,1+(m*256))*cell(21,1+(m*256))
cell(57,1+(m*256))=cell(27,1+(m*256))*cell(21,1+(m*256))

for q = 2 to 128 do
cell(52,q+(m*256))=cell(22,q+(m*256))*cell(21,q+(m*256))+cell(52,q-1)
cell(53,q+(m*256))=cell(23,q+(m*256))*cell(21,q+(m*256))+cell(53,q-1)
cell(54,q+(m*256))=cell(24,q+(m*256))*cell(21,q+(m*256))+cell(54,q-1)
cell(55,q+(m*256))=cell(25,q+(m*256))*cell(21,q+(m*256))+cell(55,q-1)
cell(56,q+(m*256))=cell(26,q+(m*256))*cell(21,q+(m*256))+cell(56,q-1)
cell(57,q+(m*256))=cell(27,q+(m*256))*cell(21,q+(m*256))+cell(57,q-1)

```

```

end for

for r=1 to 128 do

if cell(52,r)<=(cell(52,128+(m*256)))/2 then
cell(62,m+1) = cell(21,r+(m*256))
end if
if cell(53,r)<=(cell(53,128+(m*256)))/2 then
cell(63,m+1) = cell(21,r+(m*256))
end if
if cell(54,r)<=(cell(54,128+(m*256)))/2 then
cell(64,m+1) = cell(21,r+(m*256))
end if
if cell(55,r)<=(cell(55,128+(m*256)))/2 then
cell(65,m+1) = cell(21,r+(m*256))
end if
if cell(56,r)<=(cell(56,128+(m*256)))/2 then
cell(66,m+1) = cell(21,r+(m*256))
end if
if cell(57,r)<=(cell(57,128+(m*256)))/2 then
cell(67,m+1) = cell(21,r+(m*256))
end if
end for
end for

```

```

cell(12,1)="MED FREQ"

```

```

cell(12,2)=MEAN(col(62))
cell(12,3)=MEAN(col(63))
cell(12,4)=MEAN(col(64))
cell(12,5)=MEAN(col(65))
cell(12,6)=MEAN(col(66))
cell(12,7)=MEAN(col(67))

```

APPENDIX F

SAS ANOVA/MANOVA/POST-HOC PROGRAM


```

data lift; title 'ANALYSIS OF VARIANCE';
input sub    posture time  TESMAV    LESMAV    VLMAV    TESFreq
        LESFreq    VLFreq    dstrength    sstrength    fatigue Peakvertacc
        HandForce    PeakFlex    PeakExtVel    PeakShear    PeakCom
        PeakMom    IMoment Flx Knee Duration;
cards;

```

```

proc glm data=lift;
class sub posture fatigue time;
model TESMAV    LESMAV    VLMAV    TESFreq    LESFreq
        VLFreq    dstrength    fatigue Peakvertacc    HandForce    PeakFlex
        PeakExtVel    PeakShear    PeakCom    PeakMom    IMoment Flx Knee
Duration = posture sub(posture) time time*posture;
random sub(posture)/test;
*lsmeans posture/pdiff adjust=tukey;
manova h=posture e=sub(posture);
manova h=posture time time*posture;
run;

```

```

proc mixed data=lift;
class sub posture fatigue time;
model TESMAV = posture time time*posture;
random sub(posture);
run;

```

```

proc mixed data=lift;
class sub posture fatigue time;
model LESMAV = posture time time*posture;
random sub(posture);
lsmeans posture time/pdiff adjust=tukey;
run;

```

```

proc mixed data=lift;
class sub posture fatigue time;
model VLMAV = posture time time*posture;
random sub(posture);
run;

```

```

proc mixed data=lift;
class sub posture fatigue time;
model TESFreq = posture time time*posture;
random sub(posture);
run;

```

```

proc mixed data=lift;
class sub posture fatigue time;

```

```

model LESFreq = posture time time*posture;
random sub(posture);
run;
proc mixed data=lift;
class sub posture fatigue time;
model VLFreq = posture time time*posture;
random sub(posture);
lsmeans time/pdiff adjust=tukey;
run;
proc mixed data=lift;
class sub posture fatigue time;
model dstrength = posture time time*posture;
random sub(posture);
lsmeans time*posture/pdiff adjust=tukey;
run;
proc mixed data=lift;
class sub posture fatigue time;
model sstrength = posture time time*posture;
random sub(posture);
lsmeans time/pdiff adjust=tukey;
run;
proc mixed data=lift;
class sub posture fatigue time;
model fatigue = posture time time*posture;
random sub(posture);
lsmeans time/pdiff adjust=tukey;
run;
proc mixed data=lift;
class sub posture fatigue time;
model Peakvertacc = posture time time*posture;
random sub(posture);
run;
proc mixed data=lift;
class sub posture fatigue time;
model HandForce = posture time time*posture;
random sub(posture);
run;
proc mixed data=lift;
class sub posture fatigue time;
model PeakFlex = posture time time*posture;
random sub(posture);
lsmeans posture/pdiff adjust=tukey;
run;
proc mixed data=lift;
class sub posture fatigue time;
model PeakExtVel = posture time time*posture;

```

```

random sub(posture);
run;
proc mixed data=lift;
class sub posture fatigue time;
model PeakShear = posture time time*posture;
random sub(posture);
run;
proc mixed data=lift;
class sub posture fatigue time;
model PeakCom = posture time time*posture;
random sub(posture);
run;
proc mixed data=lift;
class sub posture fatigue time;
model PeakMom = posture time time*posture;
random sub(posture);
run;
proc mixed data=lift;
class sub posture fatigue time;
model IMoment = posture time time*posture;
random sub(posture);
run;
proc mixed data=lift;
class sub posture fatigue time;
model Flx = posture time time*posture;
random sub(posture)/;
lsmeans posture/pdiff adjust=tukey;
run;
proc mixed data=lift;
class sub posture fatigue time;
model Knee = posture time time*posture;
random sub(posture);
lsmeans posture/pdiff adjust=tukey;
run;
proc mixed data=lift;
class sub posture fatigue time;
model Duration = posture time time*posture;
random sub(posture);
lsmeans posture/pdiff adjust=tukey;
run;

quit

```

APPENDIX G

SAS CANONICAL CORRELATION ANALYSES PROGRAM

```

data liftall; title 'CANCORR ALL';
input sub      posture time  TESMAV    LESMAV    VLMAV    TESFreq
      LESFreq    VLFreq    dstrength  sstrength  fatigue Duration
Peakvertacc HandForce PeakFlex PeakExtVel PeakShear PeakCom
      PeakMom    IMoment Flx Knee;
cards;

```

```

proc cancorr data=liftall all;
var time      TESFreq    LESFreq    VLFreq    dstrength    fatigue ;
with TESMAV    LESMAV    VLMAV    Duration Peakvertacc HandForce
      PeakFlex    PeakExtVel PeakShear PeakCom    PeakMom
      IMoment Flx Knee;
run;

```

```

data semisquat; title 'CANCORR semisquat';
input sub      posture time  TESMAV    LESMAV    VLMAV    TESFreq
      LESFreq    VLFreq    dstrength  sstrength  fatigue Duration
Peakvertacc HandForce PeakFlex PeakExtVel PeakShear PeakCom
      PeakMom    IMoment Flx Knee;
cards;

```

```

proc cancorr data=semisquat all;
var time      TESFreq    LESFreq    VLFreq    dstrength    fatigue ;
with TESMAV    LESMAV    VLMAV    Duration Peakvertacc HandForce
      PeakFlex    PeakExtVel PeakShear PeakCom    PeakMom
      IMoment Flx Knee;
run;

```

```

data semistoop; title 'CANCORR semistoop';
input sub      posture time  TESMAV    LESMAV    VLMAV    TESFreq
      LESFreq    VLFreq    dstrength  sstrength  fatigue Duration
Peakvertacc HandForce PeakFlex PeakExtVel PeakShear PeakCom
      PeakMom    IMoment Flx Knee;
cards;

```

```

proc cancorr data=semistoop all;
var time      TESFreq    LESFreq    VLFreq    dstrength    fatigue ;
with TESMAV    LESMAV    VLMAV    Duration Peakvertacc HandForce
      PeakFlex    PeakExtVel PeakShear PeakCom    PeakMom
      IMoment Flx Knee;
run;

```

```

data stoop; title 'CANCORR stoop';
input sub      posture time  TESMAV    LESMAV    VLMAV    TESFreq
        LESFreq    VLFreq    dstrength  sstrength  fatigue Duration
Peakvertacc  HandForce  PeakFlex    PeakExtVel  PeakShear  PeakCom
        PeakMom    IMoment Flx Knee;
cards;

proc cancorr data=stoop all;
var time      TESFreq    LESFreq    VLFreq    dstrength    fatigue ;
with TESMAV    LESMAV    VLMAV    Duration Peakvertacc HandForce
        PeakFlex    PeakExtVel  PeakShear  PeakCom    PeakMom
        IMoment Flx Knee;
run;

quit

```

APPENDIX H

SAS PRINCIPAL FACTORS ANALYSES PROGRAM

```

data liftall; title 'FACTOR ALL';
input sub    posture time  TESMAV    LESMAV    VLMAV    TESFreq
        LESFreq    VLFreq    dstrength    sstrength    fatigue Duration
Peakvertacc HandForce PeakFlex PeakExtVel PeakShear PeakCom
        PeakMom    IMoment Flx Knee;
cards;

```

```

proc factor data=liftall method=prin scree rotate=varimax ev;
var time    TESMAV    LESMAV    VLMAV    TESFreq    LESFreq
        VLFreq    dstrength    fatigue Duration    Peakvertacc HandForce
        PeakFlex    PeakExtVel PeakShear PeakCom    PeakMom
        IMoment Flx Knee ;
run;

```

```

data semisquat; title 'FACTOR semisquat';
input sub    posture time  TESMAV    LESMAV    VLMAV    TESFreq
        LESFreq    VLFreq    dstrength    sstrength    fatigue Duration
Peakvertacc HandForce PeakFlex PeakExtVel PeakShear PeakCom
        PeakMom    IMoment Flx Knee ;
cards;

```

```

proc factor data=semisquat method=prin scree rotate=varimax ev;
var time    TESMAV    LESMAV    VLMAV    TESFreq    LESFreq
        VLFreq    dstrength    fatigue Duration    Peakvertacc HandForce
        PeakFlex    PeakExtVel PeakShear PeakCom    PeakMom
        IMoment Flx Knee ;
run;

```

```

data semistoop; title 'FACTOR semistoop';
input sub    posture time  TESMAV    LESMAV    VLMAV    TESFreq
        LESFreq    VLFreq    dstrength    sstrength    fatigue Duration
Peakvertacc HandForce PeakFlex PeakExtVel PeakShear PeakCom
        PeakMom    IMoment Flx Knee ;
cards;

```

```

proc factor data=semistoop method=prin scree rotate=varimax ev;
var time    TESMAV    LESMAV    VLMAV    TESFreq    LESFreq
        VLFreq    dstrength    fatigue Duration    Peakvertacc HandForce
        PeakFlex    PeakExtVel PeakShear PeakCom    PeakMom
        IMoment Flx Knee ;
run;

```



```

data stoop; title 'FACTOR stoop';
input sub      posture time  TESMAV    LESMAV    VLMAV    TESFreq
        LESFreq    VLFreq    dstrength  sstrength  fatigue Duration
Peakvertacc  HandForce  PeakFlex    PeakExtVel  PeakShear  PeakCom
        PeakMom    IMoment Flx Knee ;
cards;

proc factor data=stoop method=prin scree rotate=varimax ev;
var time      TESMAV    LESMAV    VLMAV    TESFreq    LESFreq
        VLFreq    dstrength  fatigue Duration    Peakvertacc  HandForce
        PeakFlex    PeakExtVel  PeakShear    PeakCom    PeakMom
        IMoment Flx Knee ;
run;

quit

```

APPENDIX I

AVERAGE FATIGUE ANALYSIS, KINEMATIC, AND BIOMECHANICAL FORCE DATA ACROSS ALL PARTICIPANTS

Normalized Thoracic Erector Spinae EMG Median Frequency										time	mean	mean +	mean -	stdev
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10			stdev	stdev	
.	.	.	.	.	.	.	.	.	.	0	---	---	---	---
0.469274	0.438519	0.916393	0.148036	0.729583	0.519824	0.949495	0.937282	0.951923	0.847926	1	0.690825	0.971597	0.410054	0.280771
0.511173	0.422222	1	0.741692	0.680581	0.61674	0.666667	0.864111	0.807692	0.866359	2	0.717724	0.892855	0.542592	0.175131
0.497207	0.94963	0.686885	1	0.747731	0.577093	0.974747	0.97561	0.951923	0.981567	3	0.834239	1.024265	0.644214	0.190025
0.385475	1	0.262295	0.853474	0.649728	0.422907	0.838384	0.756098	0.5	0.797235	4	0.64656	0.888443	0.404677	0.241883
0.351955	0.453333		0.351964	1	0.810573	0.883838	0.69338	0.697115	0.935484	5	0.686405	0.934642	0.438168	0.248237
0.972067	0.477037		0.542296	0.76588	1	0.944444	1	0.605769	0.935484	6	0.804775	1.016385	0.593166	0.211609
0.23743	0.397037		0.308157	0.900181	0.744493	1	0.881533	1	0.83871	7	0.700838	1.003645	0.398031	0.302807
1	0.377778		0.442598	.	0.718062	0.813131	0.630662	0.711538	1	8	0.711721	0.94071	0.482733	0.228988

Normalized Lumbar Erector Spinae EMG Median Frequency										time	mean	mean +	mean -	stdev
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10			stdev	stdev	
.	.	.	.	.	.	.	.	.	.	0	---	---	---	---
0.892508	0.272527	1	0.385507	1	1	0.389535	0.75641	0.986111	0.872247	1	0.755485	1.047796	0.463174	0.292311
0.791531	0.213187	0.564315	0.817391	0.532374	0.860465	1	0.708333	0.833333	1	2	0.732093	0.972221	0.491965	0.240128
0.915309	0.296703	0.593361	0.894928	0.717026	0.953488	0.485465	0.669872	0.875	0.726872	3	0.712803	0.923506	0.502099	0.210703
0.931596	0.243956	0.59751	1	0.318945	0.965116	0.424419	0.833333	0.898148	0.9163	4	0.712932	1.002703	0.423161	0.289771
0.775244	1	.	0.347826	0.29976	0.930233	0.5	0.679487	0.99537	0.722467	5	0.694488	0.959248	0.429728	0.26476
1	0.145055	.	0.426087	0.316547	0.843023	0.401163	1	0.842593	0.903084	6	0.653061	0.981226	0.324897	0.328164
0.794788	0.162637	.	0.307246	0.342926	0.825581	0.555233	0.836538	1	0.678414	7	0.611485	0.897584	0.325385	0.2861
0.788274	0.553846	.	0.576812	.	0.668605	0.52907	0.826923	0.824074	0.678414	8	0.680752	0.802371	0.559134	0.121618

Normalized Vastii Lateralis EMG Median Frequency										time	mean	mean +	mean -	stdev
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10			stdev	stdev	
.	.	.	.	.	.	.	.	.	.	0	---	---	---	---
1	0.879845	1	0.905759	0.949458	0.788793	0.789883	0.809028	0.857143	0.831933	1	0.881184	0.961864	0.800504	0.08068
0.661922	0.860465	0.685879	0.712042	0.758123	0.702586	0.797665	0.892361	0.597403	0.768908	2	0.743735	0.834176	0.653294	0.090441
0.843416	0.658915	0.798271	0.680628	0.877256	0.758621	0.961089	0.84375	0.887446	0.789916	3	0.809931	0.903234	0.716628	0.093303
0.701068	0.98062	0.743516	0.560209	0.722022	0.961207	0.731518	0.895833	0.831169	0.894958	4	0.802212	0.935121	0.669303	0.132909
0.772242	0.864341	.	0.298429	0.765343	0.939655	1	0.940972	0.770563	0.827731	5	0.797697	1.003443	0.591952	0.205745
0.864769	0.825581	.	0.931937	0.66065	0.831897	0.770428	0.819444	0.809524	0.886555	6	0.822309	0.898997	0.745621	0.076688
0.747331	0.976744	.	0.513089	1	0.982759	0.88716	0.913194	1	1	7	0.891142	1.055222	0.727061	0.164081
0.775801	1	.	1	.	1	0.770428	1	0.770563	0.970588	8	0.910922	1.026184	0.795661	0.115262

Dynamic Leglift Floor to Knuckle Height Strength										time	mean	mean +	mean -	stdev
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10			stdev	stdev	
1	1	1	1	1	1	1	1	1	1	0	1	1	1	0
0.98	0.91	0.99	0.89	0.95	0.85	0.92	1.01	1.48	1.02	1	1	1.177326	0.822674	0.177326
0.98	0.91	0.99	0.89	0.95	0.85	0.92	1.01	1.48	1.02	2	1	1.177326	0.822674	0.177326
0.9	0.91	1.13	0.97	0.75	0.67	0.79	1.18	1.54	1.16	3	1	1.258414	0.741586	0.258414
0.9	0.96	.	0.96	0.67	0.7	0.82	1.2	1.52	1.13	4	0.984444	1.251283	0.717606	0.266838
0.93	0.96	.	0.91	0.72	0.78	0.84	1.17	1.76	1.07	5	1.015556	1.327048	0.704063	0.311493
1	0.83	.	0.84	0.64	0.83	0.7	1.15	1.79	1.1	6	0.986667	1.332716	0.640618	0.346049
1.03	0.92	.	1.11	0.68	0.81	0.75	1.43	1.78	1.16	7	1.074444	1.426123	0.722766	0.351679
1.1	1.2	.	1.07	.	0.72	0.62	1.47	1.9	1.23	8	1.16375	1.568541	0.758959	0.404791

Static Composite Strength										time	mean	mean +	mean -	stdev
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10			stdev	stdev	
1	1	1	1	1	1	1	1	1	1	0	1	1	1	0
0.95	0.86	.	0.75	0.42	0.63	0.61	0.86	1	1.06	8	0.793333	1.002139	0.584527	0.208806

Subjective Fatigue Rating										time	mean	mean +	mean -	stdev
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10			stdev	stdev	
1	1	3	1	0	2	0	0	0	0	0	0.8	1.832796	-0.232796	1.032796
1	2	4	1	5	4	2	2	0	1	1	2.2	3.819328	0.580672	1.619328
3	3	4	1	6	6	4	2	0	3	2	3.2	5.132184	1.267816	1.932184
3	3	6	1	7	7	5	3	1	5	3	4.1	6.333582	1.866418	2.233582
3	3	10	1	8	7	5	3	1	5	4	4.6	7.588868	1.611132	2.988868
4	2	10	1	9	7	6	4	3	6	5	5.2	8.136362	2.263638	2.936362
5	4	10	1	9	7	7	3	4	6	6	5.6	8.35681	2.84319	2.75681
5	4	10	1	10	8	7	4	5	6	7	6	8.828427	3.171573	2.828427
6	4	10	1	10	8	8	4	6	6	8	6.3	9.130391	3.469609	2.830391

Normalized Thoracic Erector Spinae Mean Absolute Value										time	mean	mean +	mean -	stdev
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10			stdev	stdev	
.	.	.	.	.	.	.	.	.	.	0	---	---	---	---
0.116651	0.174614	0.030857	0.697627	1	0.271298	0.895958	0.854534	0.590863	1	1	0.56324	0.945489	0.180991	0.382249
0.2189	1	0.084837	0.058042	0.198498	0.484602	0.499948	0.802187	0.623216	0.853073	2	0.48233	0.8183	0.14636	0.33597
0.487749	0.016132	0.070616	0.006862	0.892604	0.661518	0.63337	0.802511	0.819696	0.7612	3	0.515226	0.86791	0.162542	0.352684
1	0.015881	1	0.007245	0.012739	0.848192	0.612129	1	0.899834	0.895137	4	0.629116	1.069785	0.188447	0.440669
0.66279	0.141431	.	0.214873	0.015328	0.362078	0.591146	0.846835	0.878043	0.954173	5	0.518522	0.865834	0.17121	0.347312
0.292871	0.49944	.	0.589455	0.021694	0.642206	1	0.728079	0.742091	0.913748	6	0.603287	0.906541	0.300033	0.303254
0.431793	0.852382	.	1	0.013711	0.634098	0.584745	0.823026	0.539653	0.961596	7	0.649	0.957149	0.340851	0.308149
0.367682	0.649997	.	0.443598	.	1	0.841044	0.928087	1	0.785766	8	0.752022	0.995889	0.508154	0.243868

Normalized Lumbar Erector Spinae Mean Absolute Value										time	mean	mean +	mean -	stdev
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10			stdev	stdev	
.	.	.	.	.	.	.	.	.	.	0	---	---	---	---
0.612569	0.303133	0.277592	0.133999	0.057294	0.082514	0.592174	0.658314	0.736277	0.626136	1	0.408	0.67169	0.144311	0.26369
0.771099	0.33208	1	0.108196	0.048776	0.094259	0.293733	0.571946	0.691336	0.628859	2	0.454028	0.779474	0.128583	0.325446
0.859277	0.487038	0.132442	0.086676	0.025614	0.343161	0.642796	0.738247	0.909275	1	3	0.522453	0.883692	0.161214	0.361239
0.866287	0.313025	0.733094	0.012027	0.209005	0.741859	1	0.717092	0.881473	0.742576	4	0.621644	0.947948	0.295339	0.326305
0.72436	0.162637	.	0.162316	1	0.405971	0.64658	0.690518	0.922843	0.738513	5	0.605971	0.907927	0.304014	0.301957
0.748019	0.242009	.	0.09519	0.148432	0.961487	0.619857	1	1	0.563574	6	0.597619	0.961823	0.233415	0.364204
1	0.70024	.	0.149023	0.200313	1	0.570383	0.879041	0.890009	0.638739	7	0.66975	0.988682	0.350818	0.318932
0.473439	1	.	1	.	0.685997	0.581104	0.890457	0.870635	0.714046	8	0.77696	0.971112	0.582807	0.194153

Normalized Vastii Lateralis Mean Absolute Value										time	mean	mean +	mean -	stdev
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10			stdev	stdev	
.	.	.	.	.	.	.	.	.	.	0	---	---	---	---
0.151103	0.689543	0.849071	0.043108	1	1	0.772171	1	0.714165	0.663293	1	0.688245	1.026624	0.349867	0.338379
0.591328	0.494969	1	0.071707	0.921318	0.876235	1	0.703023	1	0.789516	2	0.744809	1.040441	0.449178	0.295632
1	1	0.74128	0.085856	0.382772	0.968713	0.986372	0.828904	0.604497	0.498863	3	0.709726	1.022238	0.397214	0.312512
0.542934	0.962271	0.698165	0.133984	0.471021	0.807903	0.74667	0.697572	0.582157	1	4	0.664268	0.916196	0.412339	0.251928
0.60319	0.505705	.	0.560417	0.412555	0.791296	0.987255	0.559647	0.632032	0.636139	5	0.632026	0.800436	0.463617	0.168409
0.61864	0.530554	.	0.695156	0.447445	0.797019	0.406701	0.8987	0.714906	0.700258	6	0.645487	0.806551	0.484422	0.161065
0.735475	0.660727	.	1	0.524004	0.881711	0.387341	0.683541	0.743039	0.835317	7	0.716795	0.901337	0.532253	0.184542
0.878933	0.433933	.	0.945039	.	0.885118	0.519378	0.643759	0.715732	0.605202	8	0.703387	0.889341	0.517433	0.185954

Lift Duration (sec)										time	mean	mean +	mean -	stdev
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10			stdev	stdev	
.	.	.	.	.	.	.	.	.	.	0	---	---	---	---
2.172917	2.829167	1.679167	2.18125	3.1	1.372917	2.70625	1.645833	1.3375	1.329167	1	2.035417	2.698494	1.37234	0.663077
2.560417	2.764583	1.535417	2.520833	3.316667	1.375	1.595833	1.504167	1.35625	1.31875	2	1.984792	2.714738	1.254845	0.729947
2.304167	3.025	1.877083	2.5	2.783333	1.4	1.322917	1.422917	1.95	1.445833	3	2.003125	2.625203	1.381047	0.622078
2.310417	2.752083	2.397917	2.277083	1.8	1.40625	1.23125	1.433333	1.84375	1.758333	4	1.921042	2.417943	1.42414	0.496902
2.76875	2.239583	.	2.2	1.95	1.304167	1.883333	1.408333	1.591667	1.314583	5	1.851157	2.348134	1.354181	0.496977
2.583333	2.78125	.	2.360417	1.516667	1.322917	2.7625	1.327083	1.585417	1.710417	6	1.994444	2.613139	1.37575	0.618695
2.602083	2.583333	.	2.541667	1.566667	1.454167	1.247917	1.825	1.59375	1.525	7	1.882176	2.423456	1.340896	0.54128
2.564583	2.008333	.	2.379167	.	1.302083	2.504167	1.520833	1.96875	1.685417	8	1.991667	2.459618	1.523716	0.467951

Peak Vertical Acceleration of the Load (m/sec ²)										time	mean	mean +	mean -	stdev
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10			stdev	stdev	
.	.	.	.	.	.	.	.	.	.	0	---	---	---	---
26.6301	19.02281	13.76181	17.13203	17.39981	6.819732	13.35434	8.767697	7.46186	8.070295	1	13.84205	20.1945	7.489599	6.352449
20.88804	14.93131	21.03411	17.43955	18.20473	11.1686	7.979494	10.42741	7.981578	7.480121	2	13.75349	19.1536	8.353385	5.40011
21.62624	19.81746	19.6304	17.20434	17.99568	11.32601	7.028941	8.20818	12.08754	9.128088	3	14.40529	19.83134	8.979234	5.426055
20.28381	19.45336	15.58467	15.23714	18.2997	8.089654	7.58862	11.41198	13.57812	9.150296	4	13.86774	18.55831	9.177164	4.690571
20.23155	15.48375	.	16.0256	3.634992	8.610651	10.5247	11.01357	11.88284	7.881183	5	11.69876	16.65951	6.738006	4.960754
18.2651	18.62109	.	16.57111	20.10413	12.51273	12.67465	10.13468	8.592759	9.150287	6	14.06961	18.47189	9.66734	4.402274
20.47134	14.32802	.	17.92768	2.744604	6.828872	8.951711	10.19127	8.225658	9.979403	7	11.07206	16.63832	5.505802	5.566259
20.41856	12.88496	.	17.83748	.	8.636387	17.30997	10.84397	16.06972	9.6174	8	14.20231	18.51202	9.892588	4.309718

Average Force on the Hands During the Lift (N)										time	mean	mean +	mean -	stdev
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10			stdev	stdev	
.	.	.	.	.	.	.	.	.	.	0	---	---	---	---
248.5206	234.5892	307.6614	147.8838	315.9515	124.0813	136.4487	85.90417	136.3395	82.61831	1	181.9999	269.3776	94.62212	87.37774
240.0163	229.7633	320.0026	152.6078	305.6822	124.3325	132.4329	86.17947	137.6738	83.50377	2	181.2195	267.8075	94.63144	86.58802
240.1973	236.9873	326.598	145.8482	300.3867	124.4186	130.9129	85.1419	141.3946	83.73936	3	181.5625	269.2808	93.84419	87.71831
238.9651	235.4346	317.4566	143.2086	327.0644	126.362	132.2738	88.00639	162.6078	90.02763	4	186.1407	274.3726	97.90878	88.23191
235.5552	221.5095	.	143.2572	265.7694	125.9802	137.6389	85.76923	144.6799	85.64865	5	160.6454	225.7281	95.56258	65.08277
237.6846	232.111	.	146.7859	293.0715	141.489	138.1181	90.12247	139.3037	85.76562	6	167.1613	238.1361	96.18651	70.97481
238.0574	228.0657	.	145.0588	277.3872	123.5044	135.4373	86.68597	138.0913	85.76446	7	162.0058	230.9204	93.09122	68.9146
239.0188	220.6087	.	146.0032	.	126.2773	145.245	88.76555	147.1109	86.43217	8	149.9327	205.1079	94.7575	55.1752

Peak Lumbar Vertebral Flexion Angle During the Lift (deg)										time	mean	mean +	mean -	stdev
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10			stdev	stdev	
.	.	.	.	.	.	.	.	.	.	0	---	---	---	---
39.6754	53.64504	52.15788	70.73286	67.85731	61.65919	64.86248	59.05376	51.12021	72.61546	1	59.33796	69.62719	49.04873	10.28923
39.15252	52.1676	61.91171	69.82327	71.08451	65.00418	62.47447	57.80445	43.12607	70.4975	2	59.30463	70.5842	48.02506	11.27957
40.37229	54.71548	59.09473	66.8088	75.03161	68.34482	59.85152	60.01107	60.407	71.16279	3	61.58001	71.33119	51.82884	9.751176
43.80674	48.97578	58.78257	69.69659	72.87063	72.16651	65.7552	57.93488	45.75057	69.43979	4	60.51793	71.67239	49.36346	11.15446
39.69178	55.98475	.	67.86575	71.86018	68.00672	57.50205	58.11674	51.38317	72.42629	5	60.31527	71.11308	49.51746	10.79781
41.86095	55.36151	.	68.88382	72.41599	65.71289	67.35499	56.994	53.13721	70.37326	6	61.34385	71.45472	51.23297	10.11087
41.67847	56.57443	.	68.86181	74.2606	68.72256	67.24058	55.41078	52.74453	71.61126	7	61.90056	72.70468	51.09643	10.80413
39.16975	57.69457	.	68.28513	.	68.30508	67.09048	57.49708	55.94189	70.39064	8	60.54683	70.9351	50.15856	10.38827

Peak Lumbar Vertebral Extension Angular Velocity During the Lift (deg/sec)										time	mean	mean +	mean -	stdev
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10			stdev	stdev	
.	.	.	.	.	.	.	.	.	.	0	---	---	---	---
206.74	188.1556	222.5549	208.1321	172.2319	221.0525	200.3819	116.4629	151.2481	233.7184	1	192.0678	228.3352	155.8004	36.2674
191.4614	209.1301	239.986	218.0894	167.6798	234.0546	242.7337	116.4811	148.0137	243.2134	2	201.0843	245.3643	156.8043	44.28
224.0414	200.77	240.2	195.6241	184.687	202.4815	179.7076	134.6745	178.4295	254.3916	3	199.5007	233.7464	165.2551	34.24563
237.3785	221.2063	223.5679	186.8578	165.8078	226.818	199.9333	138.3818	150.583	271.2536	4	202.1788	243.9876	160.37	41.80881
190.2684	207.6415		183.7439	159.3804	198.4943	268.1277	135.9542	183.9945	254.2722	5	197.9863	239.7864	156.1863	41.80008
234.5928	193.0549		210.4451	181.4317	204.372	213.2222	131.7045	177.7699	256.4567	6	200.3389	236.1116	164.5661	35.77272
207.3931	235.5357		180.4874	151.3938	194.1907	197.5568	171.3634	180.1913	252.4978	7	196.7344	228.3037	165.1652	31.56925
223.0199	209.5776		187.2352	.	231.38	239.3803	189.9092	187.9023	255.1981	8	215.4503	241.3772	189.5235	25.92683

Peak Lumbar Vertebral Shear Force During the Lift (N)										time	mean	mean +	mean -	stdev
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10			stdev	stdev	
.	.	.	.	.	.	.	.	.	.	0	---	---	---	---
464.9093	403.5878	562.427	413.4194	858.1287	321.7813	378.1582	200.4099	303.2615	243.7501	1	414.9833	603.1409	226.8258	188.1576
548.6675	428.4069	772.8835	383.1603	590.7818	363.8771	344.5212	216.5938	314.5293	256.8133	2	422.0235	591.8633	252.1836	169.8399
486.7074	431.9667	946.7375	384.7438	617.9955	360.6875	335.671	214.4718	332.2656	266.2538	3	437.75	649.501	225.999	211.751
446.941	444.7904	713.5877	382.6914	608.1918	340.5539	344.0824	226.6517	374.5892	278.7457	4	416.0825	563.5283	268.6367	147.4458
492.205	435.5732		390.441	485.4471	338.6446	410.0703	228.1692	337.5808	262.7128	5	375.6493	467.8169	283.4818	92.16754
412.1811	427.9385		403.6902	723.4541	369.2715	371.3893	222.7609	308.4591	283.0281	6	391.3525	532.8317	249.8734	141.4791
490.7021	426.0981		389.7302	439.9725	310.9274	353.2778	219.322	309.5117	247.8202	7	354.1513	444.8436	263.4591	90.69222
485.3729	437.3177		384.1923	.	405.7089	423.56	227.1414	396.5747	269.1009	8	378.6211	465.5436	291.6986	86.92248

Peak Lumbar Vertebral Compressive Force During the Lift (N)										time	mean	mean +	mean -	stdev
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10			stdev	stdev	
.	.	.	.	.	.	.	.	.	.	0	---	---	---	---
15639.41	13298.28	17787.88	29634.78	18058.43	28636.86	26184.99	11469.84	16233.88	13737.77	1	19068.21	25699.36	12437.06	6631.154
25483.81	21066.06	20451.09	16862.26	14955.18	24718.51	24621.28	14108.91	18003.55	18362.28	2	19863.29	23966.33	15760.26	4103.037
19617.27	16397.76	19678.65	14511.79	22633.21	30393.5	16935.46	15854.44	27237	18302.25	3	20156.13	25318.98	14993.29	5162.847
20700.09	15730.6	16923.01	15999.01	19575.49	36593.22	24678.43	13497.97	19604.6	25557.46	4	20885.99	27611.27	14160.7	6725.284
16324.34	12530.89	.	15786.55	17984.75	28864.99	25296.22	12831.84	18481.28	16173.94	5	18252.76	23714.01	12791.5	5461.255
18519.43	14325.53	.	15554.7	17783.46	27193.55	25688.52	16098.71	19635.87	18998.37	6	19310.9	23716.22	14905.59	4405.312
17023.06	14853.44	.	20022.89	15615.86	26755.45	23982.73	21088.29	21326.32	15739.55	7	19600.84	23719.85	15481.84	4119.007
32327.98	15908.39	.	19856.2	.	27350.78	26457.18	27473.95	23740.3	18386.96	8	23937.72	29452.33	18423.1	5514.615

Peak Lumbar Vertebral Moment During the Lift (N*m)										time	mean	mean +	mean -	stdev
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10			stdev	stdev	
.	.	.	.	.	.	.	.	.	.	0	---	---	---	---
1084.549	1041.98	1684.231	2070.341	1411.578	2411.288	2035.732	965.7763	1270.532	1199.307	1	1517.531	2022.207	1012.856	504.6757
2073.596	1466.022	1640.939	1180.903	1197.522	1949.382	1715.876	1103.276	1423.061	1271.786	2	1502.236	1836.773	1167.699	334.5368
1364.069	1140.714	1505.449	1011.888	1807.933	2451.879	1305.871	1208.741	1992.429	1268.661	3	1505.763	1953.589	1057.938	447.8259
1455.354	1093.093	1373.208	1116.574	1600.727	2805.084	1880.078	1044.513	1554.841	1793.099	4	1571.657	2091.651	1051.663	519.994
1133.616	1028.478		1100.692	1260.438	2234.496	1768.47	1024.595	1283.615	1132.979	5	1329.709	1737.678	921.7394	407.9695
1282.679	989.1071		1079.1	1237.539	2026.505	1787.959	1290.352	1519.652	1322.252	6	1392.794	1725.755	1059.833	332.9611
1177.697	1033.923		1392.666	1089.247	2039.824	1862.675	2054.284	1624.31	1103.4	7	1486.447	1905.167	1067.727	418.7201
2542.292	1215.255		1386.313	.	1902.464	1841.53	1914.56	1822.22	1276.105	8	1737.592	2174.008	1301.177	436.4157

Integrated Lumbar Vertebral Moment During the Lift (N*m*s)										time	mean	mean +	mean -	stdev
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10			stdev	stdev	
.	.	.	.	.	.	.	.	.	.	0	---	---	---	---
5209.149	169.2863	6635.36	6514.454	7080.139	-809.7476	6724.852	5369.169	-92.3623	1080.886	1	3788.119	7056.555	519.682	3268.437
-1207.327	743.2349	8778.301	-54150.27	16930.12	896.8474	5590.384	6464.109	324.9522	1039.54	2	-1459.011	17838.92	-20756.94	19297.93
-45300.25	2122.789	7762.399	5479.236	14665.83	3368.712	1218.801	6875.793	5160.003	303.6284	3	165.6943	16659.92	-16328.53	16494.23
4651.33	1107.83	4423.351	4891.837	9773.207	6268.001	2489.134	5190.974	5530.606	3556.965	4	4788.324	7104.039	2472.608	2315.716
55430.73	1829.23		9291.877	5832.366	1288.365	5071.359	6428.668	2069.474	1100.96	5	9815.892	27148.31	-7516.529	17332.42
6594.31	685.0114		15041.39	10184.19	869.4204	1325.386	4399.997	2806.487	1677.748	6	4842.66	9785.038	-99.71825	4942.378
3681.66	-899.9974		4366.256	14724.09	665.1985	948.6171	3113.243	3474.659	1794.413	7	3540.905	8064.64	-982.8305	4523.735
15544.8	2676.689		2090.293	.	3103.349	753.3166	4108.481	6576.898	2751.132	8	4700.62	9395.76	5.47969	4695.14

Lumbar Vertebral Flexion Angle at the Initiation of the Lift (deg)										time	mean	mean +	mean -	stdev
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10			stdev	stdev	
.	.	.	.	.	.	.	.	.	.	0	---	---	---	---
36.9991	53.22843	39.58812	70.73286	67.85731	61.65919	64.6661	49.51262	50.94209	72.61546	1	56.78013	69.43144	44.12881	12.65132
36.32312	50.95764	52.18826	69.82327	69.05585	63.52657	62.45963	48.55144	41.40685	70.44773	2	56.47404	68.7757	44.17237	12.30167
33.77515	53.15638	53.76653	66.80532	69.27208	67.31059	58.10843	50.12113	60.19643	71.16279	3	58.36748	69.71222	47.02274	11.34474
36.14582	46.23652	53.80442	69.69659	71.77213	72.00312	65.14923	50.06503	42.05261	67.68834	4	57.46138	70.8592	44.06356	13.39782
35.9485	54.96015	.	67.86575	71.86018	68.00672	57.14429	51.65669	49.88769	64.08657	5	57.93517	69.27575	46.59459	11.34058
37.07654	54.24864	.	68.88382	72.41599	65.71289	67.35499	47.82462	51.95914	70.37326	6	59.53888	71.77081	47.30695	12.23193
40.24031	55.25959	.	68.86181	74.2606	68.6849	66.93382	49.906	51.84839	71.61126	7	60.84519	72.65116	49.03921	11.80597
33.07992	54.93481	.	68.28513	.	68.30508	67.09048	52.55417	54.96416	70.39064	8	58.70055	71.31288	46.08822	12.61233

Included Knee Angle at the Initiation of the Lift (deg)										time	mean	mean +	mean -	stdev
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10			stdev	stdev	
.	.	.	.	.	.	.	.	.	.	0	---	---	---	---
114.5966	114.9309	106.0144	158.4295	135.9449	105.3905	132.0332	82.73222	100.7169	159.3789	1	121.0168	146.052	95.98154	25.03524
104.8682	116.351	120.412	152.1624	128.1001	112.4054	123.0046	86.97967	87.45948	144.689	2	117.6432	139.0192	96.26713	21.37605
103.403	114.103	127.8707	148.9274	134.8178	120.1923	123.8659	88.84573	114.4352	144.742	3	122.1203	140.4151	103.8255	18.29478
100.0453	104.4847	128.3122	161.7836	141.0679	112.7217	132.2671	92.73921	100.7243	149.943	4	122.4089	146.1071	98.71071	23.6982
96.50678	118.2168	.	157.988	142.5481	113.8694	120.0986	93.86253	102.0739	157.6782	5	122.538	147.313	97.76306	24.77497
97.8893	115.2032	.	155.8667	145.0839	111.4335	148.6496	83.47674	102.2322	163.0825	6	124.7686	153.541	95.99625	28.77235
103.6965	117.3085	.	152.1174	151.1809	116.4036	148.9304	85.14496	104.3579	148.0047	7	125.2383	150.5454	99.93125	25.30706
95.44028	117.3842	.	149.5426	.	119.9837	144.5954	73.77065	103.4422	153.7011	8	119.7325	148.1031	91.36193	28.37059

APPENDIX J

INSTITUTIONAL REVIEW BOARD APPROVAL DOCUMENTATION

Institutional Review Board
117-B David Boyd Hall
Louisiana State University and A&M College
Baton Rouge LA 70803

(225) 388-8692

FAX: 388-6792
irb@lsu.edu

INSTITUTIONAL REVIEW BOARD

ACTION ON PROTOCOL APPROVAL REQUEST

TO: Anthony Banks, Industrial & Manufacturing Systems Engineering
Fereydoun Aghazadeh, Industrial & Manufacturing Systems Engineering

FROM: Robert C. Mathews
Chair, Institutional Review Board for Research with Human Subjects

RE: IRB# 2193

TITLE: Fatigue Effects on Manual Lifting Posture

New Protocol/Modification/Continuation : N

Review type: Full ☒ Expedited ☐ **Review date:** 12/08/2000

Approved ☒ **Disapproved** ☐

Approval Date: 12/08/2000 **Approval Expiration Date:** 12/08/2001

Risk Assessment: Minimal ☐ Uncertain ☒ Greater than Minimal ☐

Re-review frequency: (annual unless otherwise stated) ☐

Number of subjects approved: 10

By: Robert C. Mathews, Chairman Robert C Mathews

PRINCIPAL INVESTIGATOR: PLEASE READ THE FOLLOWING – Continuing approval is CONDITIONAL on:

1. Adherence to the approved protocol, familiarity with, and adherence to the ethical standards of the Belmont Report, and LSU's Assurance of Compliance with DHHS regulations for the protection of human subjects*
2. Prior approval of a change in protocol, including revision of the consent documents or an increase in the number of subjects over that approved.
3. Obtaining renewed approval (or submittal of a termination report), prior to the approval expiration date, upon request by the IRB office (irrespective of when the project actually begins); notification of project termination.
4. Retention of documentation of informed consent and study records for at least 3 years after the study ends.
5. Continuing attention to the physical and psychological well-being and informed consent of the individual participants including notification of new information that might affect consent.
6. A prompt report to the IRB of any adverse event affecting a participant potentially arising from the study.
7. Notification of the IRB of a serious compliance failure.
8. SPECIAL NOTE:

**All investigators and support staff have access to copies of the Belmont Report, LSU's Assurance with DHHS, DHHS (45 CFR 46) and FDA regulations governing use of human subjects, and other relevant documents in print in this office or on our World Wide Web site at <http://www.osr.lsu.edu/osr/comply.html>*

aaprnew.wpd

Institutional Review Board
203 B-1 David Boyd Hall
Louisiana State University and A&M College
Baton Rouge LA 70803
irb@lsu.edu

(225) 578-8692

FAX: 578-6792

LSU IRB
ACTION ON PROTOCOL APPROVAL REQUEST

TO: Anthony Banks, Industrial & Manufacturing Systems Engineering
Fereydoun Aghazadeh, Industrial & Manufacturing Systems Engineering

FROM: Robert C. Mathews, Chairman
Institutional Review Board for Research with Human Subjects

RE: IRB# 2193 DATE: 07/09/2001

TITLE: "Fatigue Effects on Manual Lifting Posture"

New Protocol/Modification: M

Review type: Full _____ Expedited X Review date: 07/02/2001

Approved X Disapproved _____

Approval Date: 07/02/2001 Approval Expiration Date: 07/02/2002

Re-review frequency: (annual unless otherwise stated) _____

Number of subjects approved: 10

By: Robert C. Mathews

PRINCIPAL INVESTIGATOR: PLEASE READ THE FOLLOWING -- Continuing approval is **CONDITIONAL** on:

1. Adherence to the approved protocol, familiarity with, and adherence to the ethical standards of the Belmont Report, and LSU's Assurance of Compliance with DHHS regulations for the protection of human subjects*
2. Prior approval of a change in protocol, including revision of the consent documents or an increase in the number of subjects over that approved.
3. Obtaining renewed approval (or submittal of a termination report), prior to the approval expiration date, upon request by the IRB office (irrespective of when the project actually begins); notification of project termination.
4. Retention of documentation of informed consent and study records for at least 3 years after the study ends.
5. Continuing attention to the physical and psychological well-being and informed consent of the individual participants including notification of new information that might affect consent.
6. A prompt report to the IRB of any adverse event affecting a participant potentially arising from the study.
7. Notification of the IRB of a serious compliance failure.
8. SPECIAL NOTE:

**All investigators and support staff have access to copies of the Belmont Report, LSU's Assurance with DHHS, DHHS (45 CFR 46) and FDA regulations governing use of human subjects, and other relevant documents in print in this office or on our World Wide Web site at <http://www.osr.lsu.edu/osr/comply.html>*

VITA

Anthony Banks was born in Zachary, Louisiana, on August 31, 1973. He received a bachelor's degree in electrical engineering at Southern University, Baton Rouge, in July 1996. He worked as a telecommunications design engineer for U S WEST Communications in Littleton, Colorado, until he enrolled in the Department of Industrial and Manufacturing Systems Engineering at Louisiana State University in August 1997. He received a master's degree in industrial engineering in May 2002. He worked as a research assistant in the Department of Orthopaedic Surgery at the Louisiana State University Health Sciences Center, New Orleans, Louisiana, during his graduate program.

Anthony is a student member of the Human Factors and Ergonomics Society, Institute of Industrial Engineers, Institute of Electrical and Electronics Engineers, and National Society of Black Engineers. He has been an EIT (Engineer-In-Training) since 1999. The degree of Doctor of Philosophy will be conferred at the May 2003 commencement.