Abstract

Nay, D. Todd. *Predicting Trunk Kinematics from Static Task Parameters.* (Under the direction of Dr. Gary A. Mirka.)

Many of the current ergonomic assessment tools available to industry take static “snapshots” of manual material handling (MMH) tasks to assess the hazards of a job. These tools are valuable to industry in that they provide a quick and inexpensive assessment of the task. However, these tools do not evaluate the trunk kinematics occurring during the task. As previous research has shown, trunk kinematics play an important role in assessing the stress placed on a person’s low back. The goal of this study was to provide a model that predicts the trunk kinematics as a result of static task parameter inputs.

A three-dimensional electrogoniometer worn on the subject’s low back (Lumbar Motion Monitor (LMM)) was used to record the effects of task parameters on trunk kinematics during a lifting task. Task parameters consisted of the inputs to the NIOSH Lifting Equation: the beginning and ending asymmetry location (five levels), horizontal distance (two levels), vertical height (three levels), and weight (two levels). Study results showed a good ability to predict the trunk kinematics in the sagittal plane, but a very low ability in the coronal and transverse planes. Using the results of this study to calculate the LMM Model’s Probability of High Risk Group Membership (PHRGM) resulted in an average absolute error of 8.07. Improvements in the ability to accurately predict the PHRGM were achieved when the MMH lifts evaluated were kept within the parameters of
this research. The results of this research provide ergonomists with trunk kinematics information from the static task parameters that can be used during the ergonomic assessment of a MMH lift.
Predicting Trunk Kinematics from Static Task Parameters

By
D. Todd Nay

A thesis submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the Degree of Master of Science.

Department of Industrial Engineering
Raleigh, North Carolina
2002

Approved by:

Dr. Gary A. Mirka
Chairman of Advisory Committee

Dr. David A. Dickey
Minor Representative

Dr. Carolyn M. Sommerich
Biography

David Todd Nay was born May 24, 1971 in Rock Island, Illinois. His family moved to the Washington, D.C. area in 1975, where he graduated from high school in June 1989. After high school, Todd enrolled at Virginia Tech, graduating with a Bachelor of Science in Ocean Engineering in May 1994. After graduation from Virginia Tech, Todd worked as a reliability engineer in Washington, D.C.

Todd started his graduate studies in Industrial Engineering at North Carolina State University in the fall of 1997. His concentration has been Ergonomics, with a minor in Interdisciplinary Studies. His area of interests has been in the field of occupational ergonomics and the ergonomic design of products. From September 1999 to March 2001 Todd took time off from his studies to work as an Ergonomist at the US Army Center for Health Promotion and Preventive Medicine in Edgewood, Maryland. He returned to Raleigh, North Carolina in April 2001 to complete his degree and to work as a Human Factors Engineer at IBM, Corp in Research Triangle Park, North Carolina.
Contents

LIST OF TABLES .................................................. V

LISTS OF FIGURES ............................................... VI

LISTS OF EQUATIONS .............................................. VII

1 INTRODUCTION ..................................................... 1

1.1 LOW BACK WMSDs .............................................. 2
1.2 RISK FACTORS FOR LOW BACK WMSDs ......................... 2
1.3 METHODS OF ANALYZING JOBS FOR INJURY POTENTIAL .......... 4
  1.3.1 COMPUTER-AIDED SYSTEMS ................................ 4
  1.3.2 MANUAL SYSTEMS ......................................... 6
1.4 THE ROLE OF TRUNK DYNAMICS ................................ 12
1.5 TRUNK MOTION PREDICTION STUDIES ........................... 15
1.6 STUDY OBJECTIVE .............................................. 18

2 METHODS .......................................................... 19

2.1 SUBJECTS ........................................................ 19
2.2 EXPERIMENTAL DESIGN ........................................ 20
  2.2.1 INDEPENDENT VARIABLES ................................. 20
  2.2.2 DEPENDENT VARIABLES ................................. 21
  2.2.3 EXPERIMENTAL DESIGN ................................. 21
2.3 EQUIPMENT ....................................................... 22
  2.3.1 LUMBAR MOTION MONITOR .............................. 22
  2.3.2 HEART RATE MONITOR .................................... 24
  2.3.3 ASYMMETRIC REFERENCE FRAME ......................... 24
  2.3.4 EXPERIMENTAL LIFTING ENVIRONMENT .................... 25
2.4 EXPERIMENTAL PROCEDURES .................................. 28
2.5 DATA PROCESSING .............................................. 31
  2.5.1 LMM DATA PROCESSING .................................... 31
  2.5.2 HEART RATE MONITOR .................................... 41
  2.5.3 ASYMMETRIC REFERENCE FRAME ......................... 41
2.6 MODEL VALIDATION ............................................ 41
List of Tables

TABLE 1. SUBJECT POPULATION INFORMATION ........................................... 19
TABLE 2. LIST OF POSSIBLE REGRESSION PREDICTORS ......................... 40
TABLE 3. SIGNIFICANT PREDICTOR VARIABLES ..................................... 44
Lists of Figures

FIGURE 1. LMM BEING WORN BY A SUBJECT. 23
FIGURE 2. LIFTING STATION WITH BOX ON THE GROUND. 26
FIGURE 3. LIFTING STATION WITH BOX ON A STAND. 27
FIGURE 4. GRAPH OF POSITION DATA FILE. 33
FIGURE 5. GRAPH OF VELOCITY DATA FILE. 34
FIGURE 6. GRAPH OF ACCELERATION DATA FILE. 35
FIGURE 7. GRAPH OF THE ABSOLUTE VELOCITY. 37
FIGURE 8. GRAPH OF THE ABSOLUTE ACCELERATION. 38
FIGURE 9. ACTUAL VS. PREDICTED PHRGM FOR EVERY LIFT 49
FIGURE 10. ACTUAL VS. PREDICTED PHRGM FOR LIFTS THAT DO NOT GO THROUGH THE MID-SAGITTAL PLANE 50
FIGURE 11. ACTUAL VS. PREDICTED PHRGM FOR LIFTS THAT GO THROUGH THE MID-SAGITTAL PLANE 51
FIGURE 12. ACTUAL VS. DIRECT PHRGM FOR EVERY LIFT. 53
FIGURE 13. ACTUAL VS. DIRECT PHRGM FOR LIFTS NOT THROUGH THE MID-SAGITTAL PLANE. 54
FIGURE 14. ACTUAL VS. DIRECT FOR LIFTS THAT GO THROUGH THE MID-SAGITTAL PLANE. 55
## Lists of Equations

<table>
<thead>
<tr>
<th>EQN.</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SAGITTAL POSITION</td>
<td>45</td>
</tr>
<tr>
<td>2</td>
<td>SAGITTAL VELOCITY</td>
<td>45</td>
</tr>
<tr>
<td>3</td>
<td>SAGITTAL ACCELERATION</td>
<td>45</td>
</tr>
<tr>
<td>4</td>
<td>CORONAL POSITION</td>
<td>46</td>
</tr>
<tr>
<td>5</td>
<td>CORONAL VELOCITY</td>
<td>46</td>
</tr>
<tr>
<td>6</td>
<td>CORONAL ACCELERATION</td>
<td>46</td>
</tr>
<tr>
<td>7</td>
<td>TRANSVERSE POSITION</td>
<td>47</td>
</tr>
<tr>
<td>8</td>
<td>TRANSVERSE VELOCITY</td>
<td>47</td>
</tr>
<tr>
<td>9</td>
<td>TRANSVERSE ACCELERATION</td>
<td>47</td>
</tr>
<tr>
<td>10</td>
<td>AVERAGE TRANSVERSE VELOCITY</td>
<td>48</td>
</tr>
<tr>
<td>11</td>
<td>LMM PHRGM DIRECT</td>
<td>52</td>
</tr>
</tbody>
</table>
1 Introduction

In November of 2000 the United States Occupational Health and Safety Administration (OSHA) issued a final Ergonomics Program standard (OSHA, 29 CFR 1910.900). The purpose of the standard was to “address the significant risk of employee exposure to ergonomic risk factors in jobs in general industry workplaces” (OSHA 2000 p.68262). This standard was a result of OSHA’s extensive review of the scientific evidence on work-related musculoskeletal disorders (WMSDs) and the economical cost of these injuries to American businesses.

As a result of their review, OSHA determined that “(1) There is a positive relationship between work-related musculoskeletal disorders and employee exposure to workplace risk factors, and (2) ergonomics programs and specific ergonomic interventions can substantially reduce the number and severity of these injuries” (OSHA 2000 p.68263). In studying the economic effects of WMSDs, OSHA determined that they account for one-third of all occupational injuries and illnesses reported to the Bureau of Labor Statistics (BLS) and one out of three dollars spent for workers’ compensation. This results in an annual cost to American businesses in excess of $15 billion.

In issuing the standard, OSHA’s goal was to reduce the number of reported work-related musculoskeletal disorders occurring annually in the United States. This was to be achieved through the establishment of ergonomic programs at American businesses. The ergonomic programs would work to reduce an employee’s exposure to the identified WMSD risk factors through education, medical management, and the ergonomic design of work environments. While the standard was repealed in April of 2001, the work done by
OSHA in its 10-year study has shown the tremendous impact of WMSDs on American workers and the advantages of ergonomics in reducing workplace injuries.

1.1 Low Back WMSDs

WMSDs can affect the neck, shoulders, elbows, wrists, fingers, back, knees, ankles, and feet. However, the most costly and most prevalent body part affected is the lower back. The incidence of low back WMSDs in the United States work force has become a major problem for industry and insurance companies. In a summary of epidemiological studies, Andersson (1984) found prevalence rates ranging from 12.0% to 30.2%. Additionally, ranges of lifetime incidence were 48.8% to 69.9%. Webster and Snook (1994) reported that 16% of all workers’ compensation claims were a result of low back WMSDs. The low back pain claims accounted for 33% of all claim costs. The total costs for all low back WMSD claims was found to be divided into 32.4% for medical costs and 65.8% for indemnity costs. Due to these factors, industry has been working to identify methods of reducing low back WMSDs.

1.2 Risk Factors for Low Back WMSDs

In order for American companies to reduce the occurrence of low back WMSDs, they need to understand the causative factors of back injuries. In their review of the research on low back WMSDs, OSHA found that there existed,
“Convincing evidence from the confluence of many investigations on biomechanical models, laboratory research and epidemiology studies that work related risk factors including (1) heavy physical work, (2) lifting and forceful movements, (3) bending, twisting, and awkward positions, and (4) static work positions ... can increase the risk of back disorder[s]” (OSHA 2000 p. 68483).

In addition to the risk factors identified in OSHA’s proposed standard, Marras et al. (1993) illustrated the importance of the dynamics of the torso in relation to low back injury risk. Specifically, Marras et al found that five task parameters could be used to distinguish between manual material handling (MMH) tasks which were classified as having a low or high risk of causing low back disorders. These parameters include the lifting frequency, load moment, trunk lateral velocity, trunk twisting velocity, and the trunk sagittal position.

These risk factors are all common in general industry. They are especially common in MMH work. If a work environment could be designed to reduce or eliminate an employee’s exposure to these risk factors, it would help to reduce their probability of incurring a low back WMSD. This has been shown in numerous ergonomic intervention studies reviewed by OSHA for their proposed standard. In their review of case studies on the effectiveness of ergonomic programs, OSHA found that “ergonomic programs designed to reduce exposures to biomechanical risk factors do reduce the incidence of [W]MSDs in exposed workers” (OSHA 2000, p. 68570).

Ergonomists must understand the risk factors present during the work, the amount of time employees will spend performing the work, the types of tools used, and the materials handled by the worker. In order to design a work environment that eliminates or reduces an employee’s exposure to the WMSD risk factors, ergonomists must study the
work being performed. Collecting and understanding this information will help ergonomists design work environments that eliminate or reduce low back WMSDs.

1.3 Methods of analyzing jobs for injury potential

1.3.1 Computer-Aided Systems

Ergonomists have used a variety of methods to evaluate workstation design over the years. One of the primary methods used has been workstation mock-ups in which human subjects would evaluate the layout by performing various tasks (Woodson, 1992). A second method is a simple scaled model. Cardboard manikins are placed in the model to help ergonomists determine the workstation layout from a reach perspective. Both of these methods are effective, but their use is limited due to the costs and time associated in building them. Due to the modeling time and cost factors, it is often not possible to make a change to the design and then make a new model for reevaluation.

Another tool being used by ergonomists involves using a computer-aided design (CAD) software package to build an environment and then placing a human model in the environment to test the ergonomics of the design (Laring, 1996; Mattila, 1996; Sengupta, 1997, Ulin, 1990). This is often referred to as computer-aided ergonomics (CAE). Programs such as Autocad®, Denab®, and Mannequin® allow ergonomists to place a human form into the environment and then move it throughout the CAD model to evaluate the ergonomics of the design. The primary advantage of this method is that it can be completed more inexpensively than the traditional mock-up methods. Additionally, design
changes can be made earlier in the design process and quickly reevaluated prior to the
development of costly mock-ups.

The current problem with CAE, however, is how the movement of the human
model is determined. Most of the programs require the user to input the changes in
posture. This is completed through the operator picking a successive series of points in
space that a specific body part will move through. The CAE software then uses a
database of joint angles to determine the posture of the human model throughout the
movement. This method can be time consuming because it requires so many inputs by the
operator. It can also be inaccurate, since it is relying on the operator’s experience to
properly identify the movement of the human model

One possible method to improve the accuracy of human model movement and to
reduce the time necessary to perform sampling methods would be the use of posture
Woldstad (1997) from Texas Tech University have worked together to develop a program
that predicts two-dimensional postures during lifting tasks. The program requires the user
to input the position of the hands, the position of the feet, and anthropometric information
about the subject in order to predict the position of the knee, hip, shoulder, and elbow
joints in the sagittal plane. Their model first determines all of the possible postures, and
then selects the optimal posture by minimizing overall effort, fatigue, and maximizing
stability. This is all done through the calculation of the torque across the joints. The
Texas Tech model, however, has only met with mild success at predicting postures
(Dysart and Woldstad, 1996). Listed as sources of error were the effects of the neck and
head not considered in the model. Other sources of error were a result of the type of lift
performed by the subjects. Subjects performed a squat, stoop, or a mixture of these methods in lifts from the ground. Researchers found that the predicted values were much more representative of a stooped lift.

One shortcoming of many posture prediction models that limits their usefulness in CAE is that they do not predict posture in all three planes of the body (sagittal, coronal, and transverse). In the real world, movement is three-dimensional. When modeling in CAD, it is done in a three dimensional environment. Utilizing the results from a two dimensional model would limit its usefulness in the CAE program. A two-dimensional model would additionally eliminate the evaluation of asymmetric postures, which were listed above as a risk factor for low back WMSDs. A more useful posture prediction model would provide posture and kinematics information in all three planes.

1.3.2 Manual Systems

In addition to evaluating workstation designs before they are built, ergonomist also evaluate jobs as they are currently being performed. This is to determine whether the design of the job could be a causative factor in worker injuries. When evaluating a current job, ergonomists evaluate the presence of the previously mentioned risk factors for low back WMSDs. These evaluations can be performed through the use of ergonomic assessment tools. Ergonomic assessment tools usually involve either work sampling or work evaluation methods.

Work sampling methods require the ergonomist to watch several cycles of a job. At set intervals, the ergonomist notes what the worker is doing and how they are doing it.
This usually involves an observation on the posture that the legs, back, neck, arms, and wrists are in during the work-sampling interval. Usually an observation on the amount of weight the worker is handling and the duration of the work is recorded. Two of the most common work-sampling methods are OWAS (Karhu et al 1977) and RULA (McAtamney, 1993).

The Ovako Working Posture Analyzing System (OWAS) developed by Karhu et al. (1977) is a simple method of analyzing postures. The OWAS system requires an observer to make several instantaneous samples of the worker’s posture. The posture is described using four codes that indicate the position of the worker’s upper extremities (three levels), lower extremities (seven levels), the back (four levels), and the force. Using the four-position code, ergonomist can determine whether a job is hazardous or not and whether it should be redesigned. The major advantage of the OWAS method is that it is simple and only takes a few seconds to perform. The major disadvantage of the OWAS method, however, is the low resolution achieved in defining the postures worked. Another disadvantage of the OWAS system is the inability to evaluate the dynamic nature of the postures involved with a job.

The Rapid Upper Limb Assessment (RULA) method developed by McAtamney and Corlett (1993) builds upon the principles of the OWAS method. The RULA method expands the individual body segments of OWAS to include a posture observation for the trunk, head/neck, upper and lower arm, the wrist, the lower limbs, and the force. It also increases the resolution of the posture through a more detailed level of body part positions based upon the degree of flexion or extension observed. After recording the postures of each of the body parts a score for each body part is developed. The scores are then
inserted into a series of exertion tables with the output resulting in a recommended course of action for the task. The recommended course of actions range from “no change to the job necessary” to “change the job immediately.” The primary advantages of the RULA method over the OWAS method are the higher resolution in the definition of the posture and the evaluation of static postures. The primary disadvantage of the RULA method is the significantly longer amount of time to complete an analysis while still not addressing the dynamics of the activity.

The second variety of ergonomic assessment tools involves work evaluation methods. Work evaluation methods involve gathering measurements of a work place and then using that information to perform a biomechanical analysis of the worker performing the job. The biomechancial analysis estimates whether the job requirements exceed safe lifting limits. Two of the most common methods of work evaluation are the University of Michigan’s 3-D Static Strength Prediction Program™ (3DSSPP) (Chaffin, 1991) and the National Institute for Occupational Safety and Health’s (NIOSH) Revised Lifting Equation (Waters et al 1993).

The 3-Dimensional Static Strength Prediction Program (3DSSPP) developed by researchers at the University of Michigan is one of the more widely used ergonomic assessment tools (Chaffin and Erig, 1991). The 3DSSPP can be used to assess acute, one time manual material handling lifts. Unlike the previous methods discussed, the 3DSSPP evaluates the strength requirements to perform the task and determines the percentage of a working population that has the strength capacity to perform the task. The strength requirements to perform the task are calculated by the 3DSSPP based upon a 3-dimensional biomechanical model developed by an ergonomist using the program’s
modeling software. The following are the required inputs to the 3-dimensional biomechanical model:

- Joint angles of the upper arm, forearm, torso, the upper and lower leg,
- Height and weight of the worker,
- Weight of the object being lifted.

Using the biomechanical model, the 3DSSPP calculates the torque at the elbow, shoulder, torso, hip, knee, and ankle joints. It then compares the required torque values to an anthropometric static strength database. The outcome of the 3DSSPP is a percentage of the working population capable of generating those levels of torque. The primary advantage of the 3DSSPP is the fact that it analyzes lifts based upon strength requirements. Studies have shown that there is a high increase in worker injury when workers are required to exceed their strength capabilities (Chaffin, 1974). Chaffin (1974) found a three-fold increase in low back WMSD incidence rates when workers exceeded their strength capabilities. The primary limitation of the 3DSSPP is the fact that it does not address the risks posed by highly repetitive tasks. These tasks, while not exceeding a worker’s strength capabilities in a single lift, can still result in low back WMSDs due to the repeated loading of the spine.

A simple and popular ergonomic assessment tool is the revised National Institute of Occupational Safety and Health (NIOSH) lifting equation (Waters 1993). NIOSH’s purpose in developing the lifting equation was “to prevent or reduce the occurrence of lifting-related low back pain (LBP) among workers.” (Waters 1993, p. 750) Unlike the
3DSSPP, the revised NIOSH lifting equation can assess the risk associated with repetitive MMH lifting tasks.

In creating the revised lifting equation, NIOSH used criteria developed from biomechanical, physiological, and psychophysical research to develop the concept of a standard lift. The standard lift is defined as a lifting location that is directly in front of a worker at a height of 75 cm above the floor and 25 cm from the mid-point between the worker’s ankles. The standard lift would be performed occasionally throughout the day and would involve moving a container having good coupling and a vertical travel distance less than or equal to 25 cm. It was determined that this standard lift could be performed with a load constant (LC) of 23 kg and still be acceptable to 90% of a mixed gender population. Deviations from the standard lift, however, would result in a recommended weight limit (RWL) for the lift being less than the LC in order for the lift to remain acceptable to 90% of the mixed gender population.

The revised NIOSH lifting equation calculates the acceptable weight (recommended weight of lift or RWL) for a lift. The RWL is a product of the LC and the six multipliers. The multipliers are used to determine the impact of deviations from the standard lift and are determined through the input of the measured static task parameters at the beginning and end of the lift. The six multipliers consist of the following: the vertical location of the hands in relationship to the ground (this multiplier is referred to as VM), the horizontal distance from the center of the load to the worker’s body (HM), the angle of twist, or asymmetry, in the worker’s trunk during the lift (AM), the vertical distance the load is lifted (DM), the frequency and duration of the lifting (FM), and the
quality of the hand coupling (CM). The multipliers range in value from 0 to 1 and thus never result in the RWL being greater than the LC.

An RWL is calculated for the beginning and ending points of the lift with the lower value being used as the RWL for the MMH task. The ratio of the actual load to the RWL is called the Lifting Index (LI). A LI value less than 1 is ideal. LI values between 1 and 3 indicate an increased level of low back WMSD risk. LI values greater than 3 indicate a significant increase in low back WMSD risk (Waters 1993).

The revised NIOSH lifting equation is a valuable asset for ergonomists assessing the risk of low back WMSD associated with MMH lifting tasks. The equation has a simplified set of input variables that are easily collected with only a ruler, stopwatch, and a goniometer. It is also helpful for ergonomists that the output of the equation provides a specific weight limit for the lifting task being analyzed. In addition, the revised NIOSH lifting equation provides a method of assessing the relative level of hazard associated with a lifting task which allows tasks that need to be changed to be prioritized.

The scope of lifting tasks that the equation is valid for, however, is the primary limitation of the equation. The revised NIOSH lifting equation is not valid for lifts that are one handed, seated, kneeling, take place in extreme temperatures, or involve unexpected conditions such as slipping. The equation is also only valid for tasks that involve only lifting and lowering. It does not account for a task that involves holding, carrying, or pushing an object. Additionally, the equation does not take into consideration any of the workers’ personnel factors such as height, weight, etc. As a result, NIOSH views the equation as “only one tool in a comprehensive effort to prevent work-related low back pain and disability” (Waters 1993, p. 769).
Essentially, all of the previously mentioned ergonomic assessment tools take a static “snapshot” of the manual material handling tasks to assess the hazards of a job. These tools are valuable to industry in that they provide a quick and inexpensive assessment of the task. While the assessment tools are fairly easy to use and they provide information as to the risk associated with a lifting task, the tools do not consider the trunk dynamics that occur during the task.

1.4 The Role of Trunk Dynamics

Research has shown that the trunk dynamics play an important role in assessing the stress placed on a person’s low back (Bigos et al, 1986; Freivalds et al, 1984; McGill and Norman, 1985, OSHA 2000). Therefore, it is important for ergonomic assessment tools to also consider the trunk dynamics of MMH tasks. Researchers at The Ohio State University developed a low back WMSD risk assessment model which was developed through a multiple logistic regression of historical injury data and trunk kinematics data collected from workers performing 403 industrial tasks (Marras et al. 1993). The tasks were classified as having either a low, medium, or high risk of low back WMSD based upon injuries and employee turnover rates. The results showed that the lift frequency, the maximum sagittal angle, the average twisting velocity, the maximum lateral velocity, and the maximum moment that occurs during a lifting task were the best predictors to distinguish between tasks with a high risk of low back WMSD and a low risk of low back WMSD. The output of the model is a single value that describes the probability of high-risk group membership for the task being evaluated. This model has been proven to be a
good predictor of low back WMSDs, however, it does require the knowledge of trunk
kinematics associated with a task (OSHA, 2000).

The primary limiting factor of The Ohio State University model is the method
required to collect the trunk kinematics data. To collect that data requires special
equipment and expertise not readily available to industry. In addition, workers must wear
the equipment while they work which may result in postural changes from their normal
methods (LI 1999). Additionally, the model was developed to evaluate the trunk
dynamics involved with a MMH lifting task. Mirka et al (2000) verified that The Ohio
State University model was limited in its ability to assess the risks in tasks that were static
or that had high-forces associated with them. They suggest that this assessment tool
should be used in conjunction with the 3DSSPP and the Revised NIOSH Lifting Equation
to generate overall appreciation for the risks posed by an MMH task.

The continuous assessment of back stress (CABS) methodology developed by
Mirka et al (2000) utilizes the revised NIOSH lifting equation, the 3DSSPP, and The Ohio
State University Model to provide a comprehensive assessment of the low-back WMSD
risk associated with MMH tasks. In their study, they found that each of the methods,
while valuable in identifying certain types of MMH tasks as having a high-risk of low back
WMSD, they are not able to fully identify every high-risk task. This result supported the
research findings of Lavender et al. (1999) which also evaluated these same three
ergonomic assessment tools. Lavender et al used each of the three ergonomic assessment
tools to analyze the low back WMSD risks associated with production jobs. Their
findings showed that the intercorrelations between the assessment tools ranged from 0.21
to 0.54. It also supports the NIOSH position that the Revised NIOSH lifting equation
should be one of many ergonomic assessment tools used during an ergonomic analysis rather than the only tool used.

The CABS methodology consisted of three stages of analysis. The first stage consisted of videotaping common tasks performed in the home construction industry. The second stage consisted of a continuous coding of the videotape data. The coding system was developed specifically for the CABS methodology analysis of the home construction industry and described the worker’s posture, action, and the weight they were handling on a continuous basis. The third stage consisted of laboratory simulations of the codes recorded in the second stage. The laboratory simulations allowed for the collection of data to input into the three ergonomic assessment tools.

The completed CABS analysis provides ergonomists with a more accurate description of the hazards associated with MMH tasks. It overcomes the limitations of the previous ergonomic assessment tools through the utilization of several methods, which together, allow for the analysis of a wider range of MMH tasks. However, since the CABS methodology utilizes The Ohio State University LMM model, it still requires the collection of trunk kinematics data. As previously mentioned, the collection of this data is often too time consuming, expensive, and complicated for most industrial companies to perform.
1.5 Trunk Motion Prediction Studies

Several researchers have developed regression models that attempt to predict trunk dynamics and which could be used as inputs to some of the models previously discussed. Ferguson et al (1992) developed models to predict the range of motion, peak velocity, average velocity, and peak acceleration in the sagittal, coronal, and transverse planes. The models are based upon data collected by Ferguson et al in a study which had subjects performing lifts from either a zero asymmetry position to a non-zero asymmetry position or from a non-zero asymmetry position to a zero asymmetry position. The independent variables in the study were the task asymmetry and the task weight. In the study, all of the non-zero asymmetry positions were to the right at 30°, 60°, 90°, 120°, 150° or 180°. The study used three different weights: 14, 28, and 42 pounds. The horizontal distance (19 in.), vertical height (18 in.), vertical distance traveled (24 in.), and the lifting frequency (1 lift/min) were kept constant.

Ferguson et al reported significant R² values at the 0.05 level for their models that could predict the sagittal, coronal, and transverse range of motions and average velocities. The sagittal, coronal, and transverse range of motion R² values were 0.83, 0.63, and 0.98, respectively. The average velocities had R² values of 0.87, 0.66, and 0.87, respectively. The models to predict the sagittal and transverse peak velocities and peak accelerations gave large R² values as well. The sagittal and transverse peak velocities had R² values of 0.67 and 0.87, respectively. The sagittal and transverse peak accelerations had R² values of 0.81 and 0.98, respectively. The possible model variables were the linear and exponential asymmetrical distance, the weight, and the asymmetrical-weight interaction.
Since the models require only the task asymmetry and weight as their inputs, the Ferguson et al models provide ergonomists with a simple method to obtain the necessary trunk dynamics for input into some of the previously discussed ergonomic assessment tools. The primary limitations in using the Ferguson et al models, however, are the range of motions for which the models were developed. During the experiment the vertical and horizontal distances did not change, similar to what would be seen if someone was moving items from one conveyor belt to another. For that type of task, the models would perform well. However, the models would not be valid in tasks where the vertical and horizontal distances changed. One example of this from industry is the loading or unloading of pallets.

In another study, Harrison (1994) developed gender specific models to predict sagittal position, velocity, and acceleration given the starting height, the starting task asymmetry, and the task weight. Harrison’s models were developed for lifts that were started at heights from 25 to 65 cm and ended at the subject’s knuckle height. The lifts were started at either zero or 90 degrees asymmetry and finished at zero degree asymmetry. The possible model variables were the vertical height, the asymmetrical distance and the weight.

The Harrison models reported $R^2$ values that were lower than the Ferguson et al models. The correlations for the sagittal range of motion, velocity and acceleration were 0.6912, 0.7084, and 0.6413, respectively. The primary limitation of the Harrison model that limits its usefulness to ergonomists is the lack of predictive capability in the coronal and transverse planes. As was previously discussed, one of the risk factors for low back WMSDs is asymmetric posture. The lack of predictive capability in all three body planes
would eliminate the ability of ergonomists to analyze asymmetric trunk kinematics. The small levels of task asymmetry and horizontal distances used in the experiment also limit the usefulness of the models to ergonomists who are looking at real world MMH tasks.

Both the Ferguson et al and Harrison models are limited in their application to real world tasks due to their inability to evaluate lifting tasks that move through the zero asymmetry plane. An example of this would be the position a worker chooses when moving boxes from a conveyor to another surface. The worker could choose to face the first conveyor to lift the box and then turn their trunk 90 degrees to place the box down on another work surface. Or, the worker could choose to stand in between the two conveyors and turn their trunk 45 degrees to one side to pick up the box. The worker would then rotate their trunk through the zero asymmetry plane and place the box down on the surface at a 45 degree position on the other side.

In order to improve upon their usefulness to ergonomists evaluating typical MMH tasks, trunk kinematics prediction models need to be able to handle a wide range of task parameters. Specifically, the prediction model would need to work for a variety of horizontal and vertical distances. The prediction model would also need to handle a variety of asymmetrical positions and would need to allow for the movement of an object from one side of a person to another.
1.6 Study Objective

While dynamic information about a lift can be helpful to field ergonomists evaluating lifting tasks, collecting that data can be time-consuming and costly. In comparison, the static measurements necessary for assessment tools like the Revised NIOSH Lifting Equation can be completed quickly and at minimal costs but may overlook important information with regard to risk. A model that combines the additional predictive strength provided by the analysis of the dynamic motions with the ease of collecting static parameters would provide a more complete assessment tool for ergonomists.

The goal of this study was to develop a model that predicts trunk kinematics from static workplace variables. With minimal cost and time requirements, this model can provide ergonomist with a feasible method of understanding the dynamic trunk motions associated with a lifting task. Using the results of this model in conjunction with current ergonomic assessment tools will provide industry with an assessment method that provides a more comprehensive analysis of the risk associated with a MMH task.
2 Methods

2.1 Subjects

Thirty subjects participated on a voluntary basis for this study. The subject population consisted of 15 females and 15 males with no history of low back or knee injuries. Population information is summarized in Table 1.

Table 1. Subject population information

<table>
<thead>
<tr>
<th>Measure</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>27.7</td>
<td>5.7</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>73.4</td>
<td>17.6</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>173.04</td>
<td>9.84</td>
</tr>
<tr>
<td>Maximum Trunk Extension Torque (N-m)</td>
<td>203</td>
<td>72</td>
</tr>
<tr>
<td>Sagittal Range of Motion - Flexion (deg)</td>
<td>79.69</td>
<td>9.09</td>
</tr>
<tr>
<td>Sagittal Range of Motion - Extension (deg)</td>
<td>33.87</td>
<td>16.39</td>
</tr>
<tr>
<td>Twisting Range of Motion - to the Right Side (deg)</td>
<td>31.42</td>
<td>7.19</td>
</tr>
<tr>
<td>Twisting Range of Motion - to the Left Side (deg)</td>
<td>23.70</td>
<td>12.77</td>
</tr>
<tr>
<td>Lateral Range of Motion - to the Right Side (deg)</td>
<td>35.60</td>
<td>10.52</td>
</tr>
<tr>
<td>Lateral Range of Motion - to the Left Side (deg)</td>
<td>35.20</td>
<td>9.03</td>
</tr>
</tbody>
</table>

Subjects were instructed as to the hazards involved with this study through an Informed Consent process approved by the Institutional Review Board for Human Subjects of North Carolina State University. The subjects were free to withdraw from the study at anytime. Subjects received a North Carolina State University Ergonomics Laboratory T-shirt for participation.
2.2 Experimental Design

2.2.1 Independent Variables

The independent variables were set as the input variables of the NIOSH Lifting Equation (Waters, 1993):

1. Starting Asymmetry location of the box (5 levels)
2. Ending Asymmetry location of the box (5 levels)
3. Starting Vertical Height of the box (3 levels)
4. Ending Vertical Height of the box (3 levels)
5. Starting Horizontal Location of the box (2 levels)
6. Ending Horizontal Location of the box (2 levels)
7. Weight of the box (2 levels).

The Starting and Ending Asymmetry locations were set at -90, -45, 0, 45, and 90 degrees from the subject’s mid-sagittal plane. A negative angle indicates rotation to the subject’s left. The Starting and Ending Vertical Heights were set at 35.56 (14), 76.20 (30), and 116.84 (46) centimeters (inches) above the ground. This was the distance from the ground to the box’s handles. The Starting and Ending Horizontal locations were set at 38.10 (15) and 63.50 (25) centimeters (inches) from the mid-point between the subject’s ankles. The weight of the box was set to achieve an average NIOSH Lifting Index of 1 for the low weight and 2 for the high weight. This resulted in weights of 4.53 (10) and 9.07 (20) kilograms (pounds.) The frequency and coupling were kept constant for all subjects at 2 lifts per minute and ‘Good”, respectively.
2.2.2 Dependent Variables

The dependent variables for this experiment were variables describing trunk kinematics during the lifting activity. These measurements were the maximum position, the absolute peak velocity, and the absolute peak acceleration of the lumbar trunk in the sagittal, coronal, and transverse planes.

2.2.3 Experimental Design

The experiment was a split plot design utilizing a central composite arrangement to reduce the number of lifts required by each subject without reducing the model’s predictive power. The split plot variables assigned to a subject were the horizontal and vertical ending positions. This means that for every lift the subject performed, the subject lifted a box from a random starting position to the same horizontal and vertical ending positions. While the horizontal and vertical ending positions remained constant for every lift a subject performed, the ending asymmetry location was randomized.

The thirty subjects were separated into five groups of six subjects each, with three male subjects and three female subjects in each group. Each subject within a group was randomly assigned a unique set of split plot variables, however, the split plot variables were repeated in all of the groups. This resulted in five replications of each split plot variable set.
2.3 Equipment

2.3.1 Lumbar Motion Monitor

The Lumbar Motion Monitor (LMM) (Chattecx Corp., Chattanooga, TN) was used to collect the trunk kinematics data during the lifting activities. The LMM is an exoskeleton that is worn on a person’s back and is secured to the torso using a shoulder harness and a waist belt as shown in Figure 1. The harness and belt design allowed the subjects to wear the LMM without any impediment to their trunk motions. The exoskeleton captures the subject’s lumbar motion, recording the time-dependent position of the lumbar spine in the sagittal, coronal, and transverse planes. These position data are then used to calculate the instantaneous velocity and acceleration of the lumbar spine. Studies have shown the LMM to be accurate and its results reproducible (Gill and Callaghan, 1996; Marras et al, 1992).
Figure 1. LMM being worn by a subject.
2.3.2 Heart Rate Monitor

A Polar Heart Rate Monitor System (Polar Electro Inc., Kempele, Finland) was used to record the subjects’ heart rate during the experiment. The system consisted of a sensor/transmitter that strapped around the subject’s chest. A watch worn by the researcher received the transmitted information. The subject’s heart rate was read off of the watch and then recorded on paper.

2.3.3 Asymmetric Reference Frame

An Asymmetric Reference Frame (ARF) connected to a KIN/COM dynamometer was used to record the subject’s maximum trunk extension torque while in a static, sagittally symmetric, 30 degree flexed position (Marras et al 1989). The ARF’s design allows researchers to restrain the subjects’ lower extremity, thus only allowing for trunk motion. By centering the rotating arm of the KIN/COM at the subject’s L5/S1, it allowed for the collection of the trunk extension torque around the L5/S1. During data collection, the trunk extension torque value was read directly off of the KIN/COM screen by the researchers.
2.3.4 Experimental Lifting Environment

In order to keep the lifting environment consistent across subjects, a lifting station was built. The lifting station can be seen in Figure 2. Every subject performed his or her lifts in this lifting station. The station consisted of a platform where the boxes being lifted were placed and a recessed cutout area where the subjects stood.

The recessed cutout area had floor markers to indicate where a subject should place his or her feet. Through strictly enforcing the subject’s feet placement during the lift, it ensured that subjects were lifting from the proper horizontal and asymmetrical positions. This was important in order to maintain the NIOSH parameters established for a lift. To ensure that the boxes being lifted were at the correct location, the lifting station had box outlines marked on the floor. The box outlines can be seen in Figures 2 and 3 as the black marks on the lifting floor. Subjects lifted a box from one of the outline marks to a second outline as instructed by the researcher conducting the experiment. The box outlines further ensured that the correct NIOSH task asymmetry and horizontal positions were maintained. Depending upon the height of the lift, the boxes were placed either directly on the platform, as shown in Figure 2, or on one of two different sized stands as depicted in Figure 3. There were two boxes used during the experiment. One box was used for the low weight of 4 kg and the second box was used for the heavier weight of 9 kg. Both boxes were of similar dimensions (25.4 cm x 25.4 cm x 30.48 cm) and had hand cutouts that met NIOSH’s definition for good coupling.
Figure 2. Lifting Station with box on the ground.
Figure 3. Lifting Station with box on a stand.


2.4 **Experimental Procedures**

Subjects were required to attend a single session lasting approximately two hours. Prior to being asked to be a subject in the experiment, subjects were screened for previous back and knee injuries. Upon arrival for the experiment, subjects were given an overview of the experiment. This consisted of an explanation of the purpose of the experiment as well as fully explaining the operation and use of each piece of equipment used in the experiment. Subjects were then asked to sign the informed consent form, a copy of which can be found in Appendix A.

After subjects signed the informed consent form, anthropometric measurements were taken. Subjects were then outfitted with the heart rate monitor and their seated resting heart rate was taken. To ensure that subjects were properly warmed up, they were required to do an aerobic warm up and stretching. The aerobic warm up consisted of a brief jog through the research facility. The stretching exercises targeted the legs, the arms, and the lower back.

Next, subjects were placed in the ARF to record their maximum trunk extension moment. Subjects started in a flexed position, thirty degrees from their upright posture. The subject was then instructed to cross their arms over their chest and push against the ARF’s sensor arm. The maximum torque was read directly off of the KIN/COM’s computer. After the first exertion, subjects were given a minute break to recuperate. They were then told the results of their first attempt, and were asked to try to exceed that
result. This continued for a total of three exertions, with a minute break between each attempt.

The LMM was then placed on the subject’s torso and fitted such that it did not limit their range of motion. After properly fitting the LMM on the subject’s back, the LMM was calibrated to the subject’s posture. The calibrations consisted of determining the LMM readings in the subject’s upright, or zero degree position, and their flexed, or ninety-degree position. The zero degree position was determined by measuring the subject standing in an upright, neutral position. The ninety-degree position was measured by having the subject bend at the waist to a position where the line connecting the proximal head of the humerus and the greater trochanter were parallel with the floor. These calibration measurements were also taken after the forty-fifth and ninety-sixth lifts. This was done to quantify any gradual shifting of the LMM on the subject during the experiment.

Once the calibration measurements were taken, subjects performed six range of motion tests. The tests consisted of measuring the forward flexion range of motion, the right and left lateral range of motion, and the right and left twisting range of motion. The final measurement was an elliptical pattern to test range of motion in three dimensions. Subjects started this test by performing a forward flexion and then moving their torso counter clockwise tracing an ellipse of 3-D range of motion. In all tests, subjects were instructed to move in a smooth motion, without bouncing their bodies to increase the range.
Next, subjects were asked to perform 6 practice lifts. This was to ensure that they were performing the lift as requested and did not have any questions. Upon completion of the practice lifts, the subject’s heart rate was recorded again.

Upon completion of these preliminary tasks, the experiment’s data collection phase was started. The data collection phase consisted of having the subjects perform the 96 lifts while LMM data was collected. Other than the split plot variables (ending horizontal and asymmetry position), the task parameters for each lift were randomized for each subject. At the beginning of every lift, the subject could see the box location at the start of the lift and was told where the box was to be placed. The researcher then started recording LMM data and prompted the subject to begin the lift. If the lift was not acceptable, the box was placed back in the starting position and the lift was performed again. The lift was not acceptable if the subject lifted a box to the wrong location or started the lift prior to the start of the LMM data collection. After confirming that the lift was done properly, the researcher would then setup the beginning and ending locations for the next lift. This procedure was repeated for the first 45 lifts. The lifts during the entire experiment were kept constant at 2 lifts per minute. After the 45th lift, the subject’s heart rate was recorded. Then the LMM was calibrated again to the subject’s upright and 90 degree posture. After a minute break, the experiment continued in the same manner as before, completing the remaining lifts. After the final lift was performed, the subject’s heart rate was once again recorded and the LMM was calibrated to the subject’s upright and 90 degree posture. The LMM equipment worn by the subject was then removed. The subject then went through another series of stretches to help them cool down.
Following the stretches, the subject’s resting heart rate was monitored. The time for their resting heart rate to return to the pre-experiment resting heart rate was recorded.

### 2.5 Data Processing

#### 2.5.1 LMM Data Processing

The LMM collected data for a period of six seconds for each lift in the study. The collection period started the moment the researcher initiated the LMM recording process and then continued for six seconds. However, the actual time that the subject was holding the weight was less than the six seconds of data collected. In order to get more precise information, the data that was collected outside of the actual lifting of the weight was not included in the final data set. The reduction of the data files from the full six seconds to just the time when the weight was being lifted was completed through a series of algorithms that evaluated the starting point of the lift, the ending point of the lift and the direction of movement as recorded by the LMM. Therefore, the data file for each lift is a different size. The size depends upon the length of time it took the subject to perform the lift. A graphical representation of the sagittal data set for one lift can be seen in Figures 4, 5, and 6. The light gray line in Figure 4 shows the lumbar trunk position data collected throughout the entire six seconds. The black line shows the lumbar position during the time that the subject was actually lifting the weight. An example of the velocity data collected is shown in Figure 5. The light gray line shows the data collected throughout the
entire six seconds while the dark black line is the data collected during the time that the subject was actually lifting the weight. Figure 6 shows the acceleration data collected. Once again, the light gray line represents the data collected throughout the entire six seconds while the dark black line is the data collected during the time that the subject was actually lifting the weight. The algorithm used to reduce the data files to only the time when the weight was being held is provided in Appendix B.
Figure 4. Graph of position data file. The gray line represents the entire data collection period. The black line represents the data collected while the subject held the weight.
Figure 5. Graph of velocity data file. The gray line represents the entire data collection period. The black line represents the data collected while the subject held the weight.
Figure 6. **Graph of acceleration data file.** The gray line represents the entire data collection period. The black line represents the data collected while the subject held the weight.
Since the subjects were moving to either their left or right during the lifts, the acceleration and velocities recorded could either be positive or negative. In order to account for this, the absolute values of acceleration and velocity were used as the dependent variables. An example of the acceleration and velocity absolute data sets for one lift can be seen in Figures 7 and 8, respectively. Taking the absolute values of the data seen in Figures 5 and 6 created the data seen in Figures 7 and 8 (see also Marras et al 1993.)
Figure 7. Graph of the absolute velocity. The “X” indicates the peak absolute velocity used in the data set.
Figure 8. Graph of the absolute acceleration. The “X” indicates the peak absolute acceleration used in the data set.
Using a program written at the NC State Ergonomics Laboratory, the maximum and minimum values for each of the LMM variables were extracted from the resulting file. This program produced a report file listing each of the maximum and minimum values. The position data were then normalized relative to the 0 and 90 degree postures. This was achieved through the use of the previously mentioned normalization files.

The formatted data from the LMM along with the subject specific data collected during the experiment made up the possible regression variables. Table 2 presents a list of the possible regression variables considered during the data analysis. This information was imported into a SAS (SAS Institute, Cary, NC) program for analysis. Using the stepwise regression procedure in SAS and a biomechanical analysis of the predictor variables, a series of regression equations were developed. The biomechanical analysis used in developing the regression equations is reviewed in the Discussion section of this work.
<table>
<thead>
<tr>
<th>Predictor</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minvert</td>
<td>The minimum value between the starting and ending vertical positions of the lift. Example: starting height is 35 cm, ending height is 76 cm. Use 35 cm.</td>
</tr>
<tr>
<td>Minvert2</td>
<td>The Minvert term squared.</td>
</tr>
<tr>
<td>Maxvert</td>
<td>The maximum value between the starting and ending vertical positions of the lift. Example: starting height is 35 cm, ending height is 76 cm. Use 76 cm.</td>
</tr>
<tr>
<td>Ranvert</td>
<td>The absolute value of the difference between the starting and ending vertical positions. Example: starting height is 35 cm, ending height is 76 cm. Use 41 cm.</td>
</tr>
<tr>
<td>Minhorz</td>
<td>The minimum value between the starting and ending horizontal positions of the lift. Example: starting horizontal position is 38 cm, ending position is 63 cm. Use 38 cm.</td>
</tr>
<tr>
<td>Maxhorz</td>
<td>The maximum value between the starting and ending horizontal positions of the lift. Example: starting horizontal position is 38 cm, ending position is 63 cm. Use 63 cm.</td>
</tr>
<tr>
<td>Ranhorz</td>
<td>The absolute value of the difference between the starting and ending horizontal positions. Example: starting horizontal position is 38 cm, ending position is 63 cm. Use 25 cm.</td>
</tr>
<tr>
<td>Minasym</td>
<td>The minimum absolute value between the starting and ending asymmetrical positions of the lift. The value is in degrees from the mid-sagittal plane. Example: The starting asymmetrical position is –45 degrees, ending position is 90 degrees. Use 45 degrees.</td>
</tr>
<tr>
<td>Maxasym</td>
<td>The maximum absolute value between the starting and ending asymmetrical positions of the lift. The value is in degrees from the mid-sagittal plane. Example: The starting asymmetrical position is –45 degrees, ending position is 90 degrees. Use 90 degrees.</td>
</tr>
<tr>
<td>Ranasym</td>
<td>The absolute value of the difference between the starting and ending asymmetrical positions. The value is in degrees. Example: The starting asymmetrical position is –45 degrees, ending position is 90 degrees. Use 135 degrees.</td>
</tr>
<tr>
<td>Boxwght</td>
<td>The weight being lifted during the task.</td>
</tr>
<tr>
<td>Weight</td>
<td>Subjects weight.</td>
</tr>
<tr>
<td>Height</td>
<td>The height of the person performing the lift.</td>
</tr>
<tr>
<td>Heart</td>
<td>The time necessary for the subject’s heart rate to return to their pre-experiment’s resting heart rate.</td>
</tr>
<tr>
<td>MaxTorq</td>
<td>The subject’s maximum extension torque measured by the ARF.</td>
</tr>
<tr>
<td>Latrom</td>
<td>The subject’s range of motion in the coronal plane.</td>
</tr>
<tr>
<td>Sagrom</td>
<td>The subject’s range of motion in the sagittal plane.</td>
</tr>
<tr>
<td>Tranrom</td>
<td>The subject’s range of motion in the transverse plane.</td>
</tr>
</tbody>
</table>
2.5.2 Heart Rate Monitor

The subject’s resting seated heart rate was recorded at the beginning of the experiment. The subject’s heart rate was then recorded after the 45th lift and after the last lift. At the conclusion of the experiment, the subject’s heart rate was monitored to determine the time it took to return to the pre-experiment’s resting seated heart rate. This information was used as a possible covariate in the regression equations to be described below.

2.5.3 Asymmetric Reference Frame

The information from the ARF was read directly off of the system’s monitor. The maximum value was then used as the subject’s maximum sagittal moment. This information was also used as a possible covariate in the regression equations to be described below.

2.6 Model Validation

As a validation of the model presented in this work, a data set developed by Mirka et al (2000) was compared to this model’s predicted values. This earlier data set contains information recorded during laboratory simulations of lifts that are typical seen in the home construction industry. For each lift, information necessary to perform a revised
NIOSH lifting equation analysis was recorded along with the resulting trunk kinematics. Using this trunk kinematics data, the LMM Probability of High Risk Group Membership (PHRGM) was calculated for each lift. Thus the data set consists of the information necessary to use the regression models of the current research to predict the value for the inputs necessary to calculate the LMM PHRGM. The predicted values for the LMM Probability using the regression models of the current research (herein called “predicted”) were compared to the actual LMM PHRGM values (herein called “actual”) from the Mirka et al (2000) work to determine the accuracy of the model. The correlation and average absolute error between the predicted and the actual PHRGMs were used as a measurement of comparison.
3 RESULTS

3.1 Final Data Model

This section presents the final regression equations, which form the model to predict the lifting trunk kinematics. There are regression equations to predict the peaks of position, velocity, and acceleration in the sagittal, coronal, and transverse planes. Table 3 lists the predictor variables that were ultimately found useful in the regression equations.
Table 3. Significant predictor variables

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minvert</td>
<td>The minimum value between the starting and ending vertical positions of the lift.</td>
<td>cm</td>
</tr>
<tr>
<td>Minvert2</td>
<td>The Minvert term squared.</td>
<td>cm squared</td>
</tr>
<tr>
<td>Maxvert</td>
<td>The maximum value between the starting and ending vertical positions of the lift.</td>
<td>cm</td>
</tr>
<tr>
<td>Ranvert</td>
<td>The absolute value of the difference between the starting and ending vertical positions.</td>
<td>cm</td>
</tr>
<tr>
<td>Minhorz</td>
<td>The minimum value between the starting and ending horizontal positions of the lift.</td>
<td>cm</td>
</tr>
<tr>
<td>Maxhorz</td>
<td>The maximum value between the starting and ending horizontal positions of the lift.</td>
<td>cm</td>
</tr>
<tr>
<td>Ranhorz</td>
<td>The absolute value of the difference between the starting and ending horizontal positions.</td>
<td>cm</td>
</tr>
<tr>
<td>Minasym</td>
<td>The minimum absolute value between the starting and ending asymmetrical positions of the lift. The value is in degrees from the mid-sagittal plane.</td>
<td>Degrees</td>
</tr>
<tr>
<td>Maxasym</td>
<td>The maximum absolute value between the starting and ending asymmetrical positions of the lift. The value is in degrees from the mid-sagittal plane.</td>
<td>Degrees</td>
</tr>
<tr>
<td>Ranasym</td>
<td>The absolute value of the difference between the starting and ending asymmetrical positions. The value is in degrees.</td>
<td>Degrees</td>
</tr>
<tr>
<td>Height</td>
<td>The height of the person performing the lift.</td>
<td>cm</td>
</tr>
</tbody>
</table>
3.1.1 Sagittal Plane Models

Equation 1 is the regression equation for the maximum sagittal flexion of the trunk. The equation had an absolute average error of 10.70 degrees and an $R^2$ of 0.8137. The complete statistical analysis for this equation and equations 2-11 can be found in Appendix C.

(Eqn 1) \[ 24.95813 + 0.56752 \times \text{HEIGHT} + 0.20882 \times \text{MAXHORZ} - 1.69566 \times \text{MINVERT} + 0.00565 \times \text{MINVERT}^2 \]

Equation 2 is the regression equation for the maximum absolute sagittal velocity of the trunk. The equation had an absolute average error of 25.84 degrees per second and an $R^2$ of 0.4955.

(Eqn. 2) \[ -20.82954 + 0.43350 \times \text{HEIGHT} - 0.45962 \times \text{MINVERT} + 0.82451 \times \text{RANVERT} + 0.10104 \times \text{RANASYM} \]

Equation 3 is the regression equation for the maximum absolute sagittal acceleration of the trunk. The equation had an absolute average error of 105.02 degrees per second squared and an $R^2$ of 0.4291.

(Eqn. 3) \[ 5.47835 + 2.26090 \times \text{HEIGHT} - 5.38931 \times \text{MINVERT} + 2.21249 \times \text{RANVERT} + 0.34850 \times \text{RANASYM} + 0.02124 \times \text{MINVERT}^2 \]
3.1.2 Coronal Plane Models

Equation 4 is the regression equation for the maximum absolute side-bending position of the trunk. The equation had an absolute average error of 3.23 degrees and an \( R^2 \) of 0.1129.

(Eqn. 4) \[-19.06432 + 0.12711*\text{HEIGHT} – 0.01188*\text{MINVERT} + 0.03150*\text{MAXASYM}\]

Equation 5 is the regression equation for the maximum absolute side velocity of the trunk. The equation had an absolute average error of 5.50 degrees per second and an \( R^2 \) of 0.0746.

(Eqn. 5) \[12.26420 + 0.04403*\text{MAXASYM} – 0.06220*\text{MINVERT} + 0.02175*\text{RANASYM}\]

Equation 6 is the regression equation for the maximum absolute side acceleration of the trunk. The equation had an absolute average error of 22.09 degrees per second squared and an \( R^2 \) of 0.0492.

(Eqn. 6) \[57.90820 + 0.10546*\text{MAXASYM} – 0.20834*\text{MINVERT} + 0.10172*\text{RANASYM}\]
3.1.3 Transverse Plane Models

Equation 7 is the regression equation for the maximum absolute rotational position of the trunk. The equation had an absolute average error of 4.21 degrees and an $R^2$ of 0.0327.

(Eqn. 7)  $1.17061 + 0.04437 \times \text{MAXASYM} + 0.01832 \times \text{MINVERT}$

Equation 8 is the regression equation for the maximum absolute rotational velocity of the trunk. The equation had an absolute average error of 10.51 degrees per second and an $R^2$ of 0.0551.

(Eqn. 8)  $-2.87346 + 0.06664 \times \text{MINVERT} + 0.10745 \times \text{RANVERT} + 0.09255 \times \text{RANASYM}$

Equation 9 is the regression equation for the maximum absolute rotational acceleration of the trunk. The equation had an absolute average error of 43.05 degrees per second squared and an $R^2$ of 0.0372.

(Eqn. 9)  $8.19844 + 0.19590 \times \text{MINVERT} + 0.35519 \times \text{RANVERT} + 0.33245 \times \text{RANASYM}$
### 3.2 Validation of the Model

In order to validate the current research’s model to predict trunk kinematics, the current research’s equations were used to provide input into the LMM Model. As previously discussed, the CABS data set developed by Mirka et al (2000) is used in this validation, however, only those lifts that were similar in scope to the ones performed during this study were used. Utilizing the CABS data set, all of the inputs into the LMM risk assessment model are either known or can now be predicted from the current research’s model except for the average rotational velocity. That equation was also developed as part of this study and is presented in Equation 10. The equation had an absolute average error of 2.07 degrees per second and an $R^2$ of 0.0620.

(Eqn. 10) $-0.85821 + 0.01693 \times \text{MINVERT} + 0.03154 \times \text{RANASYM} + 0.04069 \times \text{RANVERT}$

A comparison of the actual LMM PHRGM to the current research’s predicted LMM PHRGM is shown in Figure 9. The average absolute error between the actual and the predicted PHRGMs is 8.07 with a correlation of 0.54. Figures 10 and 11 compare the actual to the predicted PHRGM for lifts that did not go through the mid-sagittal plane and lifts that did go through the mid-sagittal plane, respectively. The average absolute error between the predictive and actual PHRGM for lifts that go through the mid-sagittal plane is 5.55 with a correlation of 0.75. The average absolute error between the actual and predicted PHRGM for lifts that do not go through the mid-sagittal plane is 10.87 with a correlation of 0.18.
Figure 9. Actual vs. Predicted PHRGM for Every Lift

The Actual data represents data collected during the CABS study (Mirka et al 2000).

The Predicted data represents data predicted by the current research’s model.
Figure 10. Actual vs. Predicted PHRGM for lifts that do not go through the Mid-Sagittal Plane

The Actual data represents data collected during the CABS study (Mirka et al 2000).

The Predicted data represents data predicted by the current research’s model.
Figure 11. Actual vs. Predicted PHRGM for lifts that go through the Mid-Sagittal Plane

The Actual data represents data collected during the CABS study (Mirka et al. 2000).

The Predicted data represents data predicted by the current research’s model.
Another possible use of the data collected in this study would be the development of an equation to directly predict the LMM PHRGM (herein called “direct”). Equation 11 provides that prediction. The equation had an absolute average error of 4.19 and an $R^2$ value of 0.3461.

(Eqn. 11) $-3.78295 - 0.04210*\text{MINVERT} + 0.04957*\text{RANASYM} + 0.02693*\text{RANVERT} + 0.04678*\text{MAXHORIZ} + 0.31765*\text{HEIGHT}$

The average absolute error between the actual and the direct PHRGM is 7.57 with a correlation of 0.15. A comparison of the actual and the direct PHRGM is shown in Figure 12. Figures 13 and 14 compare the actual PHRGM versus the direct PHRGM for lifts that did not go through the mid-sagittal plane and lifts that did go through the mid-sagittal plane, respectively. The average absolute error between the actual PHRGM to the direct PHRGM by this model for lifts that go through the mid-sagittal plane is 4.42 with a correlation of 0.56. The average absolute error between the actual and the direct PHRGM for lifts that do not go through the mid-sagittal plane is 11.07 with a correlation of 0.23.
Figure 12. Actual vs. Direct PHRGM for Every Lift.

The Actual data represents data collected during the CABS study (Mirka et al 2000).

The Predicted data represents data predicted by Equation 11.
Figure 13. Actual vs. Direct PHRGM for lifts not through the Mid-Sagittal Plane.

The Actual data represents data collected during the CABS study (Mirka et al 2000).

The Predicted data represents data predicted by Equation 11.
Figure 14. Actual vs. Direct for lifts that go through the Mid-Sagittal Plane.

The Actual data represents data collected during the CABS study (Mirka et al 2000).

The Predicted data represents data predicted by Equation 11.
4 Discussion

The goal of this study was to develop a model that predicts trunk kinematics using the values of the inputs to the revised NIOSH lift equation. Those inputs consist of the following: the beginning and ending vertical height, the beginning and ending horizontal distance, the beginning and ending asymmetrical location, and the weight of the object being lifted. Equations 1-9 represent the final models that predict the trunk kinematics given the above static task parameter inputs. The equations predict the maximum position, velocity, and acceleration in the sagittal, coronal, and transverse planes based upon these static task parameter input values.

4.1 Equation Development Methodology

The regression equations were developed through a process that considered both the statistical and biomechanical perspectives on the data. The biomechanical perspective was used to determine the factors that logically would impact a person’s lifting technique and the resulting kinematics parameters. Specifically, an understanding of the impact of the various task parameters on a person’s lifting posture and motion were incorporated into the equation development. The completed biomechanical prediction equation incorporated many variables and higher order terms. In order to reduce the biomechanical prediction equations to simple models, a statistical methodology was used. The statistical methodology was used to reduce the number of terms in a model to only those which were
statistically significant. In most cases, this resulted only in the elimination of the higher order terms from the biomechanical prediction equations.

During the development of the regression equations through the biomechanical methodology, it was important to understand the factors that would influence a person’s lifting posture. When determining the person’s posture during a lift, the location of the object to be lifted at the origin and destination plays a significant role. For example, the farthest distance away from the body in a plane has a significant effect upon the amount of flexion that occurs in that plane. Using this knowledge, the minimum values (the farthest distance from an upright position) of either the starting or ending vertical height were included. Similarly, the maximum value of the starting or ending horizontal distance and the maximum absolute value of the starting or ending asymmetrical position were included. Review of the sagittal plane equations (Eqns. 1-3) in fact reveals that these variables were good predictors of sagittal plane kinematics.

The weight of the object was also believed to have some impact on the posture and kinematics assumed during a lift. It was assumed that the posture assumed during a lift would be correlated to the spinal loading and thus affected by the weight being lifted. The weight was considered in each model, however, it was determined to not be statistically significant at the p< 0.05 level in any of the models. This could be a result of either the low weight values used in this study or the small variation between the upper and lower weight limits. A heavier weight or a larger difference between the upper and lower weight limits might have shown a higher influence on trunk posture. Ferguson et al (1992) found similar results in a study that examined the effects of weight and asymmetry on the same trunk kinematics variables. Ferguson et al did not find a significant effect with weight for
the position, velocity, and acceleration in the coronal and transverse planes, however there was a significant effect in the sagittal plane.

When reviewing the data, there was a pattern of greater maximum flexion in the taller subjects than in the shorter subjects. Due to its influence on lifting posture, subject height was included in several of the equations. Analysis revealed that the height variable was statistically significant in some of the equations, particularly in the sagittal plane. Inclusion of the height variable was reasonable from a biomechanical sense as well, since the vertical task height was independent of subject height. As a result, taller subjects were farther away from the lower vertical task height, requiring them to travel through a greater range of motion than the shorter subjects.

The equations to predict the posture that were developed during the biomechanical methodology were used as the starting point in the equations to predict the trunk kinematics. Added to the list of potential predictors for the position equations were variables that could have an effect on the trunk speed and acceleration during a lift. When determining the parameters which most influence the speed and accelerations that a person would lift with, it was determined that the distance the object was moved might play an important role. Therefore, in the biomechanical development of the equations to predict the velocity and acceleration in each plane, the range of vertical, horizontal, and asymmetrical motion was included. It was believed that the greater the range of movement for an object, the quicker the person would move. This idea was supported by Ferguson et al (1992) who reported that asymmetry has significant effect on the sagittal and transverse velocities and accelerations. In the final model these variable were found to be predictive of these motion variables.
The equation to predict posture in the sagittal plane (Eqn. 1) performed quite well and has a high $R^2$ value indicating a good ability for predicting the posture. Ferguson et al (1992) reported an equation to predict sagittal posture with a similar $R^2$ value. Harrison (1994) also developed models to predict male and female sagittal positions. The current model’s $R^2$ was higher than both of those reported by Harrison. It should be noted that the current study’s model has equal or greater predictive capability than the Ferguson et al and Harrison models over a much greater range of 3-D lifting configurations.

The current study’s equations to predict the peak sagittal velocity (Eqn. 2) and acceleration (Eqn. 3) did not have the same level of $R^2$ values as the equation to predict sagittal position. However, they did perform better than the current study’s equations to predict velocity and acceleration in the coronal and transverse planes. When comparing Equations 3 and 4 to other work the results were mixed. The Ferguson et al models achieved $R^2$ values that were much higher than the current study’s $R^2$ values. However, the Harrison models reported $R^2$ values that were slightly lower. One possible reason for this difference could be the number of different vertical heights used in each of the studies. The Ferguson et al study, which resulted in the highest $R^2$ values, had subjects lift from a single vertical height. The current study, which had the second highest $R^2$ values of the three studies, had subjects lifting from three different starting heights. In comparison, Harrison’s study had five different vertical starting heights. The increased level of vertical starting heights would result in greater lifting motion variability. This increase in lifting variability would make it harder to accurately predict the trunk kinematics information.

The $R^2$ values for the equations to predict motion in the coronal and transverse planes were quite low. This was not totally unexpected. Predicting motion in the
transverse and coronal planes can be quite difficult due to the high subject variability in the lifting motion. When a person has to lift an item, the sagittal motions they use in picking up the item are highly influenced by the vertical and horizontal location of the item as well as the height of the person. However, the motions in the transverse and coronal planes are much more dependent upon individual variability in technique. This is especially true when the object is not directly in front of them. If an object was to the side, the person could twist their trunk to pick up the item. Or, they could keep their trunk relatively straight and only bend over sideways to pick up the item. However, they could also use a combination of side bending and twisting. A person could also use various levels of pelvic twists when lifting weights that are not in front of them. It is this variability in the lifting methods that make it so difficult to accurately predict the rotational and transverse motions people will use when lifting.

Granata et al (1999) examined the variability of trunk kinematics, kinetics, and spinal loading during MMH tasks. Their study had subjects performing 10 repetitions of a MMH lifting tasks which involved two levels of box weight (13.6 and 27.3 kg), two levels of task asymmetry (0 and 60 degrees), and two levels of lifting velocity (preferred, and faster than preferred). They found that the variability in trunk kinematics was significantly dependent upon the task parameters, especially the task asymmetry. Granata et al concluded that the “performance of identical lifting tasks does not necessarily produce similar lifting kinetics or kinematics.” (Granata et al 1999, 371) The current research had lifting tasks repeated, however, as evidenced by the Granata et al study, this does not guarantee that similar trunk kinematics were recorded. This is especially true with the current research since most of the lifts performed involved some level of task asymmetry.
As a result, this would increase the difficulty of the current research’s model to accurately predict the trunk kinematics.

In general, the Ferguson et al (1992) model reported much higher $R^2$ values for their models in the three planes than those found in this study. However, as previously mentioned, their models are only valid for a small number of lifting combinations. They limited their study to a single level of task vertical height and horizontal position. In addition, all of their lifts started at the mid-sagittal plane and went to some angle of asymmetry. In contrast, this study used three levels of vertical height, two levels of horizontal distance, and allowed lifts to be performed from any of the task asymmetrical positions. So, while Ferguson et al would see some level of variation within a subject’s lifts, it would not be as high as what was seen in this study. Additionally, Ferguson et al reduced a significant amount of their subject’s variation by utilizing averaged values in the development of their models. Each of their subjects performed a specific lift three times. The results of these three lifts were averaged and used during their statistical analysis. This methodology would reduce errors due to the variability in lifting motions, as previously described by Granata et al.
4.2 Model Validation

While the model does not perform that well in the actual prediction of the coronal and transverse plane trunk kinematics during a lift, it is believed that the information can still be useful as input into other models which rely on trunk kinematics information in determining the risk of WMSDs. One such model, which has been previously discussed, is the LMM model. The LMM model uses the following five input variables: peak sagittal position, peak lateral velocity, average rotational velocity, frequency of lift, and maximum moment. The output of the model is the probability of high-risk group membership for a low back WMSD.

Typically, to collect data necessary for the LMM Model, an ergonomist would need to use equipment capable of measuring and recording the trunk kinematics of a worker during a lift. This equipment could be an electrogoniometer worn on a subject’s trunk like the LMM or another motion analysis system with similar capabilities. The problem with those data collection methods, however, is that they require specialized equipment, knowledge, and time. They also can interfere with a subject’s posture, resulting in postures that are not truly representative of the task. It is hoped that the results of this work can be used as a simple method of developing the inputs to the LMM Model.

In order to test this concept, the data set collected during the previously discussed CABS methodology was used (Mirka et al 2000). In their study, Mirka et al, had subjects simulate MMH tasks common to the home construction industry in a laboratory setting. During their simulations the subjects were outfitted with the LMM and were lifting from measured starting and ending positions. This allowed Mirka et al. to perform Revised
NIOSH Lifting Equation calculations and develop the LMM PHRGM. For this study, the CABS’ Revised NIOSH Lifting Equation inputs were used to predict the trunk kinematics information, which were then used as inputs to the LMM Model. The predicted PHRGM values were then compared to the CABS’ measured PHRGM values. A total of 57 lifts are used from the CABS data set. The 57 lifts were selected because they were similar to the lifts performed in this study.

In order to use the LMM model, a prediction for the average rotational velocity during a lift was also needed. In order to accomplish this, an additional regression equation was developed to perform this analysis. Equation 10 was developed to predict the average rotational velocity. In developing Equation 10, the same biomechanical methodology previously discussed was used. As a result, the average rotational velocity equation incorporated the same variables as the equation that predicted the maximum absolute rotational velocity (Equation 8).

The results of the comparison between the actual PHRGM to the predicted PHRGM can be seen in Figure 9. The average absolute error between the actual and predicted PHRGM is 8.07 percent. One interesting observation of the difference between the two probability values was the fact that the predicted values only went above 60 percent risk three times and in fact mainly predicted a probability of high risk group membership in the 50 percent range. This is a function of the types of lifts being evaluated.

After analysis of the results, the most significant trend observed was the asymmetrical locations of the lift. In the current study, all of the lifts started, ended, or passed through the mid-sagittal plane. The CABS data included lifts whose path did not
include the mid-sagittal plane. Figure 10 shows the actual PHRGM versus the predicted PHRGM for lifts that go through the mid-sagittal plane. As can be seen, the predicted values do a much better job on this data subset. The average absolute error between the actual PHRGM and the predicted PHRGM is now 5.55 percent for lifts that go through the mid-sagittal plane. This is a 30 percent reduction in the original error. For comparison, Figure 11 shows the actual PHRGM versus the predicted PHRGM for lifts that do not go through the mid-sagittal plane. The average absolute error between the actual PHRGM to the predicted PHRGM is 10.87 percent for the lifts that do not go through the mid-sagittal plane.

Also of interest was the effect of asymmetric range of the CABS data set. Ferguson et al (1992) showed the significant effect that asymmetrical range has on the sagittal range of motion and the average rotational velocity, which are two of the prediction equations used in this study to predict the LMM PHRGM. The lifts performed for the current study had an asymmetrical range of 90 degrees to 135 degrees. All but six of the lifts used in the CABS data set had asymmetrical ranges that were less than 90 degrees. The six CABS’ lifts that had asymmetrical ranges between 90 and 135 degrees had an absolute average error of 5.9 percent.

Another reason for the low accuracy of this research’s predicted PHRGM could be a result of using several low performing equations to make the prediction. While the equation to predict the peak sagittal angle (Eqn. 1) was fairly accurate, the equations to predict the average rotational velocity (Eqn 10) and the peak lateral velocity (Eqn. 5) were not as accurate. Using two equations with poor prediction capabilities may result in this research’s predicted PHRGM not being able to achieve any higher level of accuracy. In
order to achieve a higher level of accuracy in a predicted PHRGM a different method was attempted.

Equation 11 predicts the PHRGM using the static task parameters as input. Now, instead of predicting the peak sagittal angle, the peak lateral velocity, and the average rotational velocity and using them as inputs into the LMM Model, the PHRGM is predicted directly. This eliminates any error effects that are a result of using several predictions to generate a final prediction. In developing Equation 11, variables that were significant in the equations to predict peak sagittal angle, lateral velocity, and average rotational velocity peak were used. By doing this, Equation 11 was taking into account variables that were important in the LMM Model. At 7.57 percent, the average absolute error was slightly better than the earlier model. A greater improvement in the average absolute error can be seen in Figure 13, which compares the two probabilities only for lifts that go through the mid-sagittal plane. The average absolute error is 4.42 percent for lifts that move through the mid-sagittal plane.

Finally, as was done previously, the effect of asymmetrical range was also evaluated. For the six lifts that had asymmetrical ranges between 90 and 135 degrees, the average absolute error was 2.77 percent. While that is a significant improvement over the other models discussed, the results should be viewed cautiously since the number of lifts was small.
4.3 Limitations

The primary limitations of this work are the ranges of the independent variables. A decrease in the average absolute error for the prediction LMM PHRGM was observed when the lifts evaluated were within the parameters of this study. The parameter limitations of this study include vertical lifting heights that ranged from a subject’s knee height to their shoulder height, horizontal distances away from the subject’s midpoint between their ankles that ranged from 38 to 64 cm, asymmetrical ranges that are between 90 and 135 degrees and that go through the mid-sagittal plane, a lifting weight less than 10 kg and the frequency in the range of two lifts per minute. Under these lifting conditions, the average absolute error was 10 percent when using the prediction equations as input to the LMM model and 5 percent when trying to predict the LMM PHRGM directly.

4.4 Future Work

Through the additional validation of the model, a detailed analysis of when the model performs poorly could be developed. This could be used to set further guidelines on when the model can be used with confidence and when it can not be used. As with any regression model, the analysis could also be used to identify the types of lifts that should be performed and added to the model’s data set to help increase its predictive powers. Specific lifts that could be added to the data set include lifts that would expand the levels of the independent variables. This would include the evaluation of lifts with greater weight, increased asymmetry locations, and a greater range of vertical and
horizontal distances. Also of interest would be lifts that filled in the spaces from the current independent variables. These might include lifts that were to a vertical distance that fell in between two vertical locations previously used or asymmetrical ranges that did not pass through the mid-sagittal plane.

One of the obstacles to overcome when trying to predict the posture was the inter-subject and intra-subject variability in the lifting techniques. This variability led to the recording of different trunk kinematics values for identical lifts. The current research’s data set could be further analyzed to determine the factors that influence the trunk kinematics’ variability. Specifically, to understand what task variables cause the greatest amount of trunk kinematics variability. This information would be useful by researchers trying to develop trunk kinematics prediction models.
5 CONCLUSION

There are many ergonomic assessment tools available that can be used to evaluate MMH lifting tasks. They include tools like the Revised NIOSH Lifting Equation, the OWAS method and the RULA method. The tools are popular with ergonomist because they provide for a quick, simple and economical method to analyze the low back WMSD risks associated with lifting tasks. However, these methods do not analyze the trunk kinematics of the lift which studies have shown to be better at identifying jobs which have low back WMSD risk associated with them. The ergonomic assessment tools currently in use that evaluate trunk kinematics information are time consuming, costly, and complex. This research was a first step at developing an ergonomic assessment tool that evaluates the trunk kinematics of a lift using a quick, simple, and cost effective methodology.

- The equations to predict the trunk kinematics in the sagittal plane performed better than the equations for the coronal and transverse planes. The equation to predict the sagittal range of motion, peak velocity, and peak acceleration had $R^2$ values of 0.81, 0.50 and 0.43, respectively.

- The absolute average error between the current research’s predicted LMM PHRGM and a measured LMM PHRGM was 8.07.

- The absolute average error between the current research’s predicted LMM PHRGM and a measured LMM PHRGM improved to 5.55 when only lifts that go through the mid-sagittal plane were evaluated.
The current research’s ability to predict the LMM PHRGM improved when the PHRGM was directly predicted instead of calculated through the predictions of the trunk kinematics. The direct PHRGM for lifts that go through the mid-sagittal plane had an average absolute error of 4.42 compared to 5.55 for the predicted PHRGM.
6 Literature Cited


Harrison, AE (1994).  **An evaluation of the dynamics of lifting under various lifting Conditions.**, Master’s Thesis, North Carolina State University, Raleigh, NC.


Appendix A:

Informed Consent Form
INFORMED CONSENT FORM

Title of Study: Development of a low back posture prediction model
Principle Investigator: D. Todd Nay
Faculty Sponsor (if applicable): Dr. Gary Mirka

Thank you for your participation in this research study. The purpose of this study is to develop a posture prediction model which can be used by ergonomists and biomechanic researchers in studying workplace design and injury prevention. The posture prediction model will provide ergonomists and scientists biomechanical data about the posture and movement characteristics of a person’s back while performing a lifting task. The model will be developed from the information collected during your experimental session as well as the other subjects in this study. One of the primary contributions of this work will be the considerable time savings to ergonomists and scientists studying low back injuries. In studying human movement, data collection is a time consuming tasks as scientist must record the postures a person works in. The posture prediction model will serve to greatly reduce the amount of time to collect data.

INFORMATION
This experiment will last approximately 3-4 hours. The experiment will run as follows:

1. The researcher will briefly introduce the purpose of this experiment.
2. You will then be introduced to the equipment that will be used in this experiment.
   a) The first piece of equipment to be used in this study is the Asymmetric Reference Frame (ARF). The ARF will be used to test your maximum strength when moving from a bent at the waist posture to an upright posture. You will be placed in the ARF in a bent posture and then asked to push against it’s arm with your back.

I understand the purpose and operation of the ARF.
   1. Subject’s Initials __________

   b) The second piece of equipment to be used in this study is the Lumbar Motion Monitor (LMM). The LMM is used to measure the movement of your back during the various lifting tasks you will be performing. The LMM is attached to your back through the use of shoulder and waist vests.

I understand the purpose and operation of the LMM.
   1. Subject’s Initials __________

   c) During the experiment you will be videotaped. The videotape will record the movement of markers placed on you. The markers will be placed on your right ankle, knee, hip, shoulder, elbow, and the back your hand. If it is necessary to attach markers to your skin, a hypoallergenic tape will be used. The video markers will be used to determine the position of your body during the lifting task.

I understand the purpose and how the markers will be placed.
   1. Subject’s Initials __________

   d) In order to track the amount of physical exertion required during the experiment, your heart rate will be measured throughout the experiment.

I understand the purpose of tracking my heart rate.
   1. Subject’s Initials __________
4. Once the experiment has been described and your questions answered, you will be asked to read and sign the Informed Consent Form.
5. The researcher will then take several anthropometric measurements for use in building the posture prediction model.
6. In order to reduce the risk of injury, the researcher will lead you through a series of stretching exercises. These exercises will target your legs, back, and arms.
7. We will now use the ARF to test your maximum strength. We will perform three of these tests. Each tests last just a few seconds.
8. We will now place the LMM on your back. The LMM should not restrict your movement. If it does, please notify the researcher.
9. We will now perform the primary part of the experiment. You will be asked to perform 92 lifts. One lift will consist of moving a box from a starting position to an ending position. The starting and ending positions are defined through the vertical, horizontal, and asymmetrical location of the box relative to your body. The possible positions include:

| Asymmetry (degrees):       | -90, -45, 0, 45, 90 |
| Horizontal (inches from the subject): | 15, 25 |
| Vertical (inches above the ground):   | 14, 30, 36 |
| Frequency of Lifts:         | Twice every minute |
| Weight of box (lb.):        | 11.75, 23.25 |

Due to the experimental design, you will only lift to certain positions.

I understand the lifting tasks I will perform.
Subject’s Initials __________

10. Once you have completed the 92 lifts, the equipment will be removed.
11. You will now be lead through a series of warm-down stretching exercises.
12. The experiment is concluded.

B. State the amount of time required of the subject per session and for the total duration of the study.
Subject will be required to attend one session lasting 3-4 hours.

**RISKS**
The primary risk associated with this experiment is low back muscle strains resulting from overexertion. To reduce this risk, you will be lead through a series of stretching exercises before and after the experiment. If you need to take a break during the experiment, please notify the investigator. In order to verify that the subject is not working at an excessive level, they will be outfitted with a heart rate monitor. The subject’s heart rate will be measured periodically during the experiment.

The hypoallergenic tape that will be used to fasten the markers has adhesive on it. If you have had an allergic reaction to such adhesives in the past, notify the investigator. Though the risk of any skin irritation occurring is very low, it is possible. If there are other reasons we should not use adhesive on your skin, notify one of the investigators prior to initiating the study.

**EXCLUSION CRITERIA**
Subjects will be excluded from this experiment for the following reasons:

1. Unable to lift 25 pounds to a height of 46 inches.
2. Currently have an injury or are experiencing pain in their knees, back, shoulders, or elbows.
3. Have ever had an injury to their knees, back, shoulders, or elbows which prevented them from working.

Subject’s Initials __________
I meet these criteria and am eligible to participate in this experiment.
Subject’s Initials __________

BENEFITS
In order for ergonomists to evaluate the hazards associated with a workstation design, they must spend considerable time collecting workstation measurements and worker postures. Collecting this data often limits the amount of workstations an ergonomists can evaluate. This research will greatly reduce the amount of time it takes to collect data, allowing for quicker and more complete evaluations of workstation design. Additionally, this work will assist biomechanic researchers in their study of workplace injury by providing a quicker method of collecting dynamic effects that occur during a lift.

CONFIDENTIALITY
The information in the study records will be kept strictly confidential. Data will be stored securely and will be made available only to persons conducting the study unless you specifically give permission in writing to do otherwise. No reference will be made in oral or written reports which could link you to the study.

COMPENSATION
For participating in this study you will receive an Ergonomics Laboratory T-shirt. If you withdraw from the study prior to its completion, you will still receive the T-shirt.

EMERGENCY MEDICAL TREATMENT (if applicable)
Medical compensation is not available.

CONTACT
If you have questions at any time about the study or the procedures, you may contact the researcher, D. Todd Nay, at 341 Riddick Hall, Box 7906, NCSU, Raleigh, North Carolina, 27695, or [919-515-7210]. If you feel you have not been treated according to the descriptions in this form, or your rights as a participant in research have been violated during the course of this project, you may contact the Dr. Gary A. Mirka, Chair of the NCSU IRB for the Use of Human Subjects in Research Committee, Box 7906, NCSU Campus.

PARTICIPATION
Your participation in this study is voluntary; you may decline to participate without penalty. If you decide to participate, you may withdraw from the study at any time without penalty and without loss of benefits to which you are otherwise entitled. If you withdraw from the study before data collection is completed your data will be returned to you or destroyed.

CONSENT
I have read and understand the above information. I have received a copy of this form. I agree to participate in this study.

Subject's signature __________________________ Date ______________
Investigator's signature __________________________ Date ______________
Appendix B: 

Data Validation 

Algorithm
This appendix describes the algorithm that was used to reduce the collected LMM data to only the time that the subject was actually performing the lift. It was performed for each lift in the data set.

Begin Data Reduction Algorithm

Is the Vert_st = Vert_end?

Yes

3

No

Locate the time that the Maximum Sagittal Angle occurs.

Is the Vert_st < Vert_end?

Yes

The end of the lift occurs at the Maximum Sagittal Angle.

No

The start of the lift occurs at the Maximum Sagittal Angle.

1

Discard all data points after the time of the Maximum Sagittal Angle.

2
1

Discard all data points prior to the time of the Maximum Sagittal Angle.

Keep the first 50 data points after the time of the Maximum Sagittal Angle.

Is the sagittal velocity < 5 deg/sec?

Yes

Keep current data point. Go to next data point.

No

Discard the remaining data points.

5
Keep the first 50 data points prior to the time of the Maximum Sagittal Angle.

Is the sagittal velocity > -5 deg/sec?

Yes

Keep current data points. Go to previous data points.

No

Discard all points prior to this time.

5
Is Vert_st < 40 inches?

Yes

Locate the time that the Maximum Sagittal Angle occurs.

No

Locate the time that the Maximum Sagittal Angle occurs.

Discard all data points whose sagittal angle is < 50% of the Maximum Sagittal Angle

Discard all data points whose sagittal angle is < 80% of the Maximum Sagittal Angle

4
Review the information from the earliest data point.

Is the sagittal velocity < 5 deg/sec?

Yes → Discard current data point. Go to next data point.

No → Review the information from the last data point.

Is the sagittal velocity > -5 deg/sec?

Yes → Discard current data point. Go to next data point.

No → End
Appendix C:

Statistical Analysis
**Equation 1: Sagittal Position**

The REG Procedure  
Model: MODEL1  
Dependent Variable: sag_pos

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>4</td>
<td>2085384</td>
<td>521346</td>
<td>3083.46</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Error</td>
<td>2824</td>
<td>477477</td>
<td>169.07830</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>2828</td>
<td>2562861</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Root MSE 13.00301  
R-Square 0.8137  
Dependent Mean 59.65107  
Adj R-Sq 0.8134  
Coef Var 21.79845

Parameter Estimates

| Variable      | DF | Parameter Estimate | Standard Error | t Value | Pr > |t| |
|---------------|----|--------------------|----------------|---------|------|---|
| Intercept     | 1  | 24.95813           | 4.99141        | 5.00    | <.0001|
| height        | 1  | 0.56752            | 0.02542        | 22.33   | <.0001|
| maxhoriz      | 1  | 0.20882            | 0.02235        | 9.34    | <.0001|
| minvert       | 1  | -1.69566           | 0.04991        | -33.98  | <.0001|
| minvert2      | 1  | 0.00565            | 0.00035108     | 16.11   | <.0001|
Equation 2: Sagittal Velocity

The REG Procedure
Model: MODEL1
Dependent Variable: sag_vel

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>4</td>
<td>3284535</td>
<td>821134</td>
<td>693.38</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Error</td>
<td>2824</td>
<td>3344317</td>
<td>1184.24816</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>2828</td>
<td>6628852</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Root MSE         | 34.41291 | R-Square | 0.4955 |
Dependent Mean   | 67.25239 | Adj R-Sq | 0.4948 |
Coeff Var        | 51.16979 |

Parameter Estimates

<table>
<thead>
<tr>
<th>Variable</th>
<th>DF</th>
<th>Parameter Estimate</th>
<th>Standard Error</th>
<th>t Value</th>
<th>Pr &gt;</th>
<th>t</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>1</td>
<td>-20.82954</td>
<td>12.71589</td>
<td>-1.64</td>
<td>0.1015</td>
<td></td>
<td></td>
</tr>
<tr>
<td>height</td>
<td>1</td>
<td>0.43350</td>
<td>0.06740</td>
<td>6.43</td>
<td>&lt;.0001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>minvert</td>
<td>1</td>
<td>-0.45962</td>
<td>0.02807</td>
<td>-16.37</td>
<td>&lt;.0001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ranvert</td>
<td>1</td>
<td>0.82451</td>
<td>0.02586</td>
<td>31.89</td>
<td>&lt;.0001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ranasym</td>
<td>1</td>
<td>0.10104</td>
<td>0.03321</td>
<td>3.04</td>
<td>0.0024</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Equation 3: Sagittal Acceleration

The REG Procedure
Model: MODEL1
Dependent Variable: sag_acc

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>5</td>
<td>42610620</td>
<td>8522124</td>
<td>424.30</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Error</td>
<td>2823</td>
<td>56699869</td>
<td>20085</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>2828</td>
<td>99310489</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Root MSE 141.72145
R-Square 0.4291
Dependent Mean 285.70626
Adj R-Sq 0.4281
Coeff Var 49.60390

Parameter Estimates

| Variable     | DF | Parameter Estimate | Standard Error | t Value | Pr > |t| |
|--------------|----|--------------------|----------------|---------|------|---|
| Intercept    | 1  | 5.47835            | 55.05483       | 0.10    | 0.9207 |
| height       | 1  | 2.26090            | 0.27781        | 8.14    | <.0001 |
| minvert      | 1  | -5.38931           | 0.54557        | -9.88   | <.0001 |
| ranvert      | 1  | 2.21249            | 0.10657        | 20.76   | <.0001 |
| ranasym      | 1  | 0.34850            | 0.13676        | 2.55    | 0.0109 |
| minvert2     | 1  | 0.02124            | 0.00383        | 5.55    | <.0001 |
Equation 4: Coronal Position

The REG Procedure
Model: MODEL1
Dependent Variable: side_pos

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>3</td>
<td>6097.02293</td>
<td>2032.34098</td>
<td>119.84</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Error</td>
<td>2825</td>
<td>47910</td>
<td>16.95925</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>2828</td>
<td>54007</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Root MSE 4.11816 R-Square 0.1129
Dependent Mean 4.71792 Adj R-Sq 0.1120
Coeff Var 87.28761

Parameter Estimates

| Variable | DF | Parameter Estimate | Standard Error | t Value | Pr > |t| |
|----------|----|--------------------|----------------|---------|------|---|
| Intercept| 1  | -19.06432          | 1.46171        | -13.04  | <.0001 |
| height   | 1  | 0.12711            | 0.00804        | 15.81   | <.0001 |
| minvert  | 1  | -0.01188           | 0.00281        | -4.23   | <.0001 |
| maxasym  | 1  | 0.03150            | 0.00397        | 7.94    | <.0001 |
Equation 5: Coronal Velocity

The REG Procedure
Model: MODEL1
Dependent Variable: side_vel

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>3</td>
<td>11796</td>
<td>3931.86131</td>
<td>75.90</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Error</td>
<td>2825</td>
<td>146349</td>
<td>51.80501</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>2828</td>
<td>158145</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Root MSE          7.19757
R-Square          0.0746
Dependent Mean    14.29021
Adj R-Sq           0.0736
Coef Var           50.36714

Parameter Estimates

| Variable  | DF | Parameter Estimate | Standard Error | t Value | Pr > |t| |
|-----------|----|--------------------|----------------|---------|------|---|
| Intercept | 1  | 12.26420           | 0.83740        | 14.65   | <.0001 |
| maxasym   | 1  | 0.04403            | 0.00736        | 5.99    | <.0001 |
| minvert   | 1  | -0.06220           | 0.00485        | -12.83  | <.0001 |
| ranasym   | 1  | 0.02175            | 0.00737        | 2.95    | 0.0032 |
**Equation 6: Coronal Acceleration**

The REG Procedure  
Model: MODEL1  
Dependent Variable: side_acc

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>3</td>
<td>126350</td>
<td>42117</td>
<td>48.75</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Error</td>
<td>2825</td>
<td>2440752</td>
<td>863.98312</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>2828</td>
<td>2567102</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Root MSE 29.39359  
R-Square 0.0492  
Dependent Mean 64.30894  
Adj R-Sq 0.0482  
Coef Var 45.70685

Parameter Estimates

| Variable      | DF | Parameter Estimate | Standard Error | t Value | Pr > |t|   |
|---------------|----|--------------------|----------------|---------|------|-----|
| Intercept     | 1  | 57.90820           | 3.41978        | 16.93   | <.0001 |
| maxasym       | 1  | 0.10546            | 0.03004        | 3.51    | 0.0005 |
| minvert       | 1  | -0.20834           | 0.01979        | -10.53  | <.0001 |
| ranasym       | 1  | 0.10172            | 0.03010        | 3.38    | 0.0007 |
Equation 7: Rotational Position

The REG Procedure  
Model: MODEL1  
Dependent Variable: rot_pos  

Analysis of Variance  

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>2</td>
<td>2868.75769</td>
<td>1434.37885</td>
<td>47.71</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Error</td>
<td>2826</td>
<td>84964</td>
<td>30.06525</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>2828</td>
<td>87833</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Root MSE 5.48318  
R-Square 0.0327  
Dependent Mean 5.73489  
Adj R-Sq 0.0320  
Coeff Var 95.61091  

Parameter Estimates  

| Variable   | DF | Parameter Estimate | Standard Error | t Value | Pr > |t|  |
|------------|----|--------------------|----------------|---------|-------|
| Intercept  | 1  | 1.17061            | 0.47919        | 2.44    | 0.0146|
| maxasym    | 1  | 0.04437            | 0.00528        | 8.40    | <.0001|
| minvert    | 1  | 0.01832            | 0.00369        | 4.96    | <.0001|
**Equation 8: Rotational Velocity**

The REG Procedure  
Model: MODEL1  
Dependent Variable: rot_vel

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>3</td>
<td>29742</td>
<td>9914.06153</td>
<td>54.88</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Error</td>
<td>2825</td>
<td>510357</td>
<td>180.65740</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>2828</td>
<td>540099</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Root MSE: 13.44089  
R-Square: 0.0551  
Dependent Mean: 14.27289  
Adj R-Sq: 0.0541  
Coeff Var: 94.17075

Parameter Estimates

| Variable   | DF | Parameter Estimate | Standard Error | t Value | Pr > |t| |
|------------|----|--------------------|----------------|---------|------|
| Intercept  | 1  | -2.87346           | 1.60441        | -1.79   | 0.0734 |
| minvert    | 1  | 0.06664            | 0.01079        | 6.18    | <.0001 |
| ranvert    | 1  | 0.10745            | 0.01006        | 10.68   | <.0001 |
| ranasym    | 1  | 0.09255            | 0.01297        | 7.14    | <.0001 |
Equation 9: Rotational Acceleration

The REG Procedure
Model: MODEL1
Dependent Variable: rot_acc

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>3</td>
<td>343026</td>
<td>114342</td>
<td>36.37</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Error</td>
<td>2825</td>
<td>8880305</td>
<td>3143.47080</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>2828</td>
<td>9223331</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Root MSE 56.06666
R-Square 0.0372
Dependent Mean 66.13326
Adj R-Sq 0.0362
Coef Var 84.77831

Parameter Estimates

| Variable     | DF | Parameter Estimate | Standard Error | t Value | Pr > |t| |
|--------------|----|--------------------|----------------|---------|------|-----|
| Intercept    | 1  | 8.19844            | 6.69254        | 1.23    | 0.2207|
| minvert      | 1  | 0.19590            | 0.04502        | 4.35    | <.0001|
| ranvert      | 1  | 0.35519            | 0.04198        | 8.46    | <.0001|
| ranasym      | 1  | 0.33245            | 0.05410        | 6.14    | <.0001|
Equation 10: Average Rotational Velocity

The REG Procedure
Model: MODEL1
Dependent Variable: avgrot

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>3</td>
<td>4114.46425</td>
<td>1371.48808</td>
<td>62.20</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Error</td>
<td>2825</td>
<td>62289</td>
<td>22.04909</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>2828</td>
<td>66403</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Root MSE       | 4.69565  |
R-Square       | 0.0620   |
Dependent Mean | 4.79379  |
Adj R-Sq       | 0.0610   |
Coeff Var      | 97.95277 |

Parameter Estimates

| Variable   | DF | Parameter Estimate | Standard Error | t Value | Pr > |t|   |
|------------|----|--------------------|----------------|---------|------|-----|
| Intercept  | 1  | -0.85821           | 0.56051        | -1.53   | 0.1259 |
| minvert    | 1  | 0.01693            | 0.00377        | 4.49    | <.0001 |
| ranasym    | 1  | 0.03154            | 0.00453        | 6.96    | <.0001 |
| ranvert    | 1  | 0.04069            | 0.00352        | 11.57   | <.0001 |
Equation 11: PHRGM Direct Prediction

The REG Procedure
Model: MODEL1
Dependent Variable: lmmprob

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>5</td>
<td>42477</td>
<td>8495.34322</td>
<td>298.78</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Error</td>
<td>2823</td>
<td>80268</td>
<td>28.43349</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>2828</td>
<td>122744</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Root MSE 5.33231 R-Square 0.3461
Dependent Mean 57.39840 Adj R-Sq 0.3449
Coeff Var 9.28999

Parameter Estimates

| Variable   | DF | Parameter Estimate | Standard Error | t Value | Pr > |t| |
|------------|----|--------------------|----------------|---------|------|---|
| Intercept  | 1  | -3.78295           | 2.05400        | -1.84   | 0.0656 |
| minvert    | 1  | -0.04210           | 0.00435        | -9.68   | <.0001 |
| ranasym    | 1  | 0.04957            | 0.00515        | 9.63    | <.0001 |
| ranvert    | 1  | 0.02693            | 0.00401        | 6.72    | <.0001 |
| maxhoriz   | 1  | 0.04678            | 0.00916        | 5.10    | <.0001 |
| height     | 1  | 0.31765            | 0.01045        | 30.40   | <.0001 |
### Mean and Standard Deviations of the Trunk Kinematics Collected

<table>
<thead>
<tr>
<th></th>
<th><strong>Sagittal</strong></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Standard Deviation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Peak Position</strong></td>
<td>61.33</td>
<td>32.38</td>
<td>4.74</td>
<td>5.53</td>
<td>57.40</td>
<td>6.55</td>
<td></td>
</tr>
<tr>
<td><strong>Peak Velocity</strong></td>
<td>67.22</td>
<td>48.15</td>
<td>14.32</td>
<td>13.73</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Peak Acceleration</strong></td>
<td>258.08</td>
<td>186.00</td>
<td>64.49</td>
<td>56.77</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Coronal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Peak Position</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Peak Velocity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Peak Acceleration</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Transverse</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Peak Position</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Peak Velocity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Peak Acceleration</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Average Velocity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>LMM PHRGM (%)</strong></td>
<td>4.76</td>
<td>4.81</td>
<td>57.40</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.55</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>