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Two- And Three-Plane Job Risk Classification Using Motion Capture: An Examination Of The Marras Et Al. Model, 1993

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TWO- AND THREE-PLANE JOB RISK CLASSIFICATION USING MOTION CAPTURE: AN EXAMINATION OF THE MARRAS ET AL. MODEL, 1993

By

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Lower Back Disorders account for 16-19% of work related claims and 33-41% of dollars paid in workers' compensation (as cited in Marras, 1999), with impacts to society approaching $100 billion dollars annually (as cited in Marras et al., 1999). Dr. William Marras engineered a device to track trunk kinematics in order to develop a Job Risk Classification Model for predicting high-risk group probability of lower back injury. The device has been validated, but other technologies such as 3-D motion capture can potentially gather the same data. This study examined the use of motion capture to apply two- and three-plane lifting tasks to the Marras model and compare results with commonly used assessment techniques. Regardless of the fact that the Marras model results were drastically different from NIOSH and RULA, motion capture was able to gather all necessary data for running the models and has a promising future in ergonomic assessments.

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LIST OF ABBREVIATIONS

CAVS	Center for Advanced Vehicular Systems
EMG	Electromyography
JRCM	Job Risk Classification Model
LBD	Lower Back Disorder
LMM	Lumbar Motion Monitor
LI	Lifting Index
MMH	Manual Material Handling
MSU	Mississippi State University
NIOSH	National Institute for Occupational Safety and Health
OSHA	Occupational Safety and Health Administration
RI	Risk Index
RULA	Rapid Upper Limb Assessment
RWL	Recommended Weight Limit

CHAPTER I

INTRODUCTION

According to the U.S. Bureau of Labor Statistics, more than 420,000 individuals missed work in 1999 due to back injury alone (as cited in Marras, 2002) triggering doctor's visits second in frequency only to the common cold (Ambrose *et al*., 2004). Deyo reported that Lower Back Disorders (LBDs) directly impact approximately 80% of the working population at some point during their career (as cited in Davis & Seol, 2005) with each individual losing an average of 6 days on the job and accounting for nearly 60% of lost workdays (Marras *et al*., 1999c; Marras, 2002). In an effort to mitigate injury risk, industry has begun investing resources in ergonomic analyses and interventions, implementing in both the design phase and existing workstations. Results of these analyses can potentially show that while certain job tasks fall within acceptable guidelines, others may exhibit gross violations of established injury risk levels. Industrial Manual Material Handling (MMH) tasks have been shown to account for the majority of these injuries due to their taxing physical nature, however, MMH remains the most popular method of material transfer (as cited in Marras *et al*., 1999c). In order for MMH tasks to be cost effective, the worker must lift the maximum weight possible while remaining below injury limits for the lower back, thus avoiding medical costs due to injury (Davis & Marras, 2000).

The National Research Council classifies risk factors for occupationally related LBDs into physical job demand factors, psychosocial factors, and individual factors (Ferguson *et al*., 2004). Physical job demand factors of MMH tasks include activities such as lifting, bending, twisting, lateral bending, maintenance of static postures, carrying of heavy loads, and combinations of such (as cited in Marras *et al*., 1999). There are a number of lower back assessment tools available for use such as the National Institute for Occupational Safety and Health (NIOSH) Lifting Guide, the Rapid Upper Limb Assessment (RULA), energy expenditure predictions, heart rate/oxygen consumption, comfort analyses, and the 3-D Static Strength Prediction Program. Whether or not these tools measure the same dimensions of lower back risk or if they are capable of adequately predicting LBD risk has encouraged additional examination (Marras *et al*., 2000) leading to the emergence of a superior model. Over a period of 20 years, the Occupational Safety and Health Administration (OSHA) and NIOSH combined in an effort to examine risk factors involved in MMH tasks and to classify over 400 MMH jobs as either high- or low-risk for LBDs. Dr. William S. Marras and colleagues from Ohio State University attempted to further classify these occupations by developing a Job Risk Classification Model, through the use of a technologically advanced device, which he termed the Lumbar Motion Monitor (LMM). While no doubt the LMM provides accurate data on spine positioning, there are other commercially available techniques that exist for collecting this same data.

Motion capture technology can record data for all the major joints of the body, as well as the face, and can interface with ergonomic evaluation software to create accurate digital human models as well as to examine loads, moments, and comfort. In the laboratory, integration of motion capture with digital human modeling software and virtual reality technology can allow examination of job tasks before they are implemented in the industrial setting (Ambrose *et al*., 2004). With adequate preparation in this laboratory environment, motion capture systems can be effectively utilized in the workplace for observation of workers during real-time MMH tasks.

This study was conducted on a simulated MMH task in the Human Systems Laboratory at the Center for Advanced Vehicular Systems (CAVS), Mississippi State University (MSU). Motion data was collected using a method capable of providing multiple sources of information for both dynamic and static analyses simultaneously, in order to compare to the Marras *et al*. 1993 Model, from now on referred to as the Jobr Risk Classification Model (JRCM) or the Marras model. Anytime new technology is introduced, it is essential to determine whether the new technology can effectively measure data using the same "ruler" as the existing technology. Just as a group of builders, who set out to build the same house with rulers of different lengths will not successfully accomplish their task unless a common measure is established, risk analyses accomplished using different techniques may produce contradictory injury risk results. The main goal of this project was to examine isolated subtasks that might normally be found as single components of an assembly line inspection task or a stocking position, in order to observe how the results of an analysis using motion capture would compare to risk classification results achieved by the Marras model, using the LMM. Motion capture technology, which is commercially available for whole system purchase or contract use, is far more affordable than the original systems that came out in the 1980s and has an incredibly broad application, even outside the occupational safety realm.

This study is relevant to industrial applications because companies are learning of the potential financial benefits that come with incorporating ergonomic practices and interventions into their workplaces. Studies that seek to decrease the negative impacts of particular tasks or workstations on the human body can reduce the number/cost of injuries on the company floor, decrease worker discomfort and fatigue, and improve productivity (Marras *et al*., 2000), thereby increasing their profit margin. Furthermore, if implemented in design stages, ergonomic analyses and interventions can potentially predict injury risks before tasks are even fully developed—allowing time for adequate and effective warehouse or plant redesign while saving tremendous amounts of money. The impact of poor, incorrect, or inadequate interventions is not only a waste of the very resources intended for preservation, but can lead to dormant musculoskeletal risks to be discovered years down the road (Marras et al., 2000) By providing multiple approaches for reaching the same conclusions (Motion capture vs. LMM), companies have more freedom for investigating existing and proposed job tasks in an effort to reduce negative physiological impacts on the body and cut down or prevent high rates of worker's compensation claims.

CHAPTER II

LITERATURE REVIEW

Lower Back Disorders

The National Safety Council identifies the back as the most frequently injured part of the body due to overexertion at 22% of 1.7 million injuries annually (NIOSH, 1994). Lifting tasks in MMH environments in particular, due to their dynamic nature and high muscle activation, pose a specific threat to loads that a healthy spine can safely tolerate. Compression and other forces on the lumbro-sacral (L5/S1) joint make it easily prone to injury (Marras *et al.*, 1992) because that region of the back has demonstrated the largest range of angular displacement in flexion and extension (as cited in Webber & Kriellaars, 2004). In an effort to mitigate these injuries, several approaches have been examined to reduce the risk of LBDs.

Research tends to support that the risk of LBD has largely to do with body postures, angles, and load arms which can be examined in a variety of ways (as cited in Ambrose *et al.*, 2004). The ergonomic techniques currently available to examine dynamic lifting have been developed in accordance with biomechanical loading principles, psychophysical and dynamic strength assessments, and kinematic evaluations based upon epidemiologic trends (Marras, 1999). Biomechanical loading, developed over 30 years ago, was designed to represent the body as a cantilever system. Many of these biomechanical models made extensive assumptions about the muscular system, ignoring and/or grossly underestimating co-contraction of antagonistic muscles (Fathallah *et al*., 1999). Electromyographic (EMG)-assisted models helped to monitor this muscle coactivation, but typically these models could only assume slow and smooth loads imposed on the body in snapshots—a series of static postures discounting inertial influences (Marras *et al*., 1992). Because spinal compression is often assumed to be the principal cause of LBD, the original NIOSH Lifting Equation (1981) examined static compressive estimates and established a 3400N "action limit" for lifting (Granata & Marras, 1999). A number of studies showed there was more to the LBD problem than compression alone.

Factors besides compression, such as shear and torsional loads, are essential to a more complete understanding of LBD risk. Herrin *et al.* found that static compression estimates actually accounted for less than 2% of variability in injury rates, while Punnet *et al*. determined that very few tasks actually had compressive forces greater than the 3400N NIOSH limit (as cited in Granata & Marras, 1999). A study by Bigos *et al*. concluded that dynamic lifts posed three times greater risk of LBD than workers in static postures (as cited in Marras *et al*., 1992) perhaps due to the significantly increased spinal compressive and shear forces (as cited in Marras, 1992). Freivalds *et al*. claimed that acceleration could effectively increase the static load on the spine by as much as 40% (as cited in Marras, 1999; Granata & Marras, 1999: Norman & McGill, 1984) while Fathallah *et al*. cited an equally high underestimation of forces and moments when applying static analyses to dynamic lifts (1999). According to Davis, performing a static analysis for a highly dynamic lift could underpredict compressive values by 60-90% and anterior-posterior shear by 150-230% (Davis & Marras, 2000). EMG-assisted models can be useful to understanding compression and shear force measurements as well as muscle activation patterns, but application of such models requires extensive expertise and according to research by Fathallah *et al*., spinal loading can be adequately assessed without the use of EMG (1999).

The second ergonomic technique for evaluating dynamic lifting is the psychophysical and dynamic strength assessment. This approach is capable of incorporating frequency of lift, duration of lift, box size, height of lift, movement distance, number of people involved, symmetric conditions, shape of object, load distribution, coupling conditions, load stability, and direction of applied force in order to design for a large percentage of the population (Marras, 1999). Dynamic strength assessments can be used to determine the whole body peak force by allowing the lifter to subjectively determine an acceptable amount of weight to be lifted. This approach however, fails to provide an accurate representation of lift rate and/or pacing—a critical omission, as it has been observed that workers may actually work beyond their physical limitations in order to increase break time (Marras, 1999).

The third technique for evaluating dynamic lifting is based on trunk kinematics and historical observation. Ferguson *et al*. developed a model which implied that low back injury risk is due almost entirely to workplace design and discounts individual differences and psychosocial factors (2004), while research conducted by Fathallah *et al*. concluded a combined model of workplace variables, subject variables, trunk kinematic variables, and measured moment variables that could be measured over time and examine compressive and shear loads would serve as the most accurate predictor of continuous spinal loading (1999). Even the 1981 NIOSH Lifting Equation, originally designed to observe static compressive loads, revised their equation in 1991 based on epidemiologic research and acknowledged the importance of incorporating asymmetry into a risk assessment (NIOSH, 1994). Similarly, Dr. William Marras and the National Research Council concluded that models considering trunk kinematics were the most effective for predicting risk of LBDs (Ferguson *et al*., 2004).

The Lumbar Motion Monitor

Dr. Marras, a pioneer in the field of dynamic lifting assessments and director of the Biodynamics Laboratory at Ohio State University, identified a number of factors which made static models inferior. He found that in dynamic lifting, trunk strength would decrease and muscle activity would increase with an increase in trunk velocity, acceleration or asymmetry (Marras *et al*., 1992). As a result, he developed a triaxial electrogoniometer that he termed the Lumbar Motion Monitor, to assess the instantaneous position, velocities, and accelerations of the thoracolumbar spine in three-dimensional space (Marras *et al*., 1993)(See Figure 1).

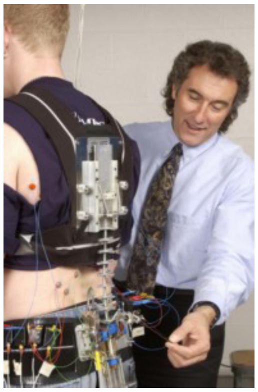


Figure 1. William S. Marras with his Lumbar Motion Monitor

(Marras, 2002)

The LMM was strapped to the pelvis and chest to shadow the movement of the spine in the sagittal, lateral, and twisting planes.

Marras and colleagues examined historical OSHA and NIOSH databases of past work-related lower back injuries and used the LMM to observe over 400 MMH jobs associated with varying degrees of risk. They observed that typically, low-risk jobs consisted of slow movement in one or two planes and produced a risk index below 30%, while high-risk jobs were associated with fast movements in all three planes and a risk index above 60% (Marras, 1999)(See Figure 2). More specifically, low-risk jobs were defined as those with at least three years of records showing no injuries and no turnover and high-risk jobs as those associated with at least 12 injuries per 200,000 hours of exposure (Marras *et al*., 1993).

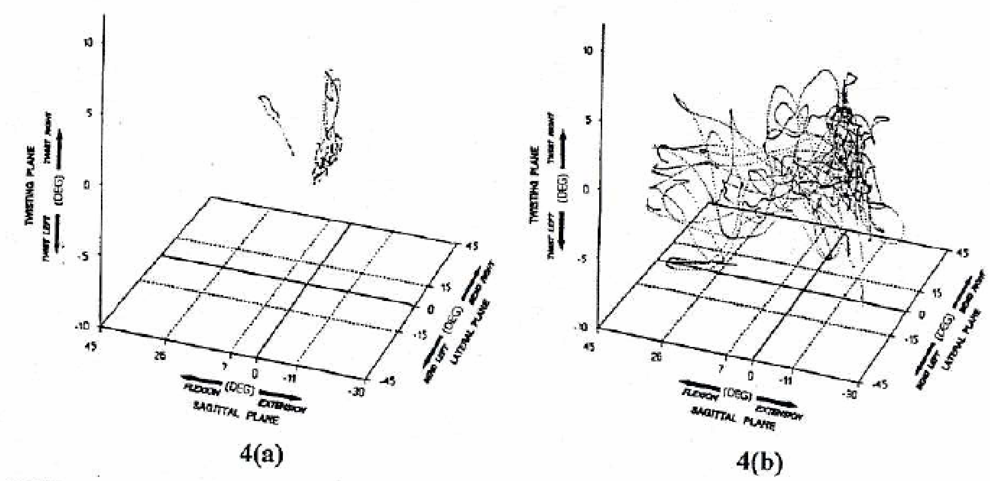


FIGURE 22.4 An example of trunk motion in a (a) low-risk and (b) high-risk job. Each point in the figure indicates the position of the thorax relative to the pelvis in three-dimensional space. The points are spaced one-sixtieth of a second apart. Thus, the more space between points the faster the motion.

Figure 2. Trunk Motion in 2- and 3- Dimensions

(Marras *et al*., 1993)

Marras and colleagues were interested in the examination of certain factors and how they effected job-risk classification. These factors, consisting of both physical job demand factors, or workplace factors, and individual trunk motion factors but excluding psychosocial influences, included: lift rate, vertical load location at origin, vertical load location at destination, vertical distance traveled by load, average weight handled, maximum weight handled, average horizontal distance between load and L5/S1 vertebrae, maximum horizontal distance between load and L5/S1 vertebrae, average moment, maximum moment, and job satisfaction, as well as maximum extension position, maximum flexion position, range of motion, average velocity, maximum velocity, maximum acceleration, and maximum deceleration in the sagittal, lateral, and twisting planes of the body (1993).

To determine if any single variable could distinguish between high- and low-risk, Marras *et al*. ran numerous univariate logistic regressions. Ultimately, they found that few individual factors were capable of discriminating well between high- and low-risk group membership, but that maximum moment yielded the highest odds ratio of the workplace factors (5.17) and sagittal velocity yielded the highest odds ratio of the trunk motion factors (3.33) (1993).

Job Risk Classification Model

Similar to linear regression, a logistic regression seeks to find the best fitting model to describe the relationship between an independent variable and a dependent variable. Logistic regression was chosen over linear regression due to the dichotomous nature of the dependent variable—classification as high-risk group membership or classification as not high-risk group membership (also referred to as low-risk), whereas the linear regression assumes a dependent variable that is continuous in nature. Both linear and logistic regressions are interested in determining the conditional mean values of the outcome or dependent variable. While a linear regression scatterplot of the expected value of the dependent variable (E(Y|x)), given the value of the independent variable can be expressed as a linear equation with specific Y-intercept and slope, the logistic regression is said to be "S-shaped", in that $0 \leq E(Y|x) \leq 1$ and approaches zero and 1 gradually (Hosmer & Lemeshow 2000). Another profound difference between linear and logistic regression is that the errors between the observed values of the dependent variable and the conditional mean follow a normal distribution, while the conditional distribution of the dependent variable in logistic regression is binomial. (Hosmer & Lemeshow 2000).

Because Marras *et al*. found the single factors of Maximum Moment and Sagittal Velocity as insufficient to fully determine risk-group membership, they turned to multiple logistic regression. The goal was to explore different combinations of factors to derive a model which had the highest predictive power for high risk group membership, hereafter referred to as Risk Index (RI) (Marras *et al*., 1993). A number of models were tested before deciding on the one model that would yield the highest odds ratio. That model, yielding an odds ratio of 10.7, incorporated the workplace factors of lift rate and maximum moment, along with individual trunk motion factors of average twisting velocity, maximum sagittal flexion, and maximum lateral velocity and is shown in Table 1. Hypothetically, manipulation of the five multiple logistic regression model variables could result in a decrease in probability of high-risk group membership by almost eleven times (Marras *et al*., 1993). While the model will not indicate what kind of ergonomic interventions to implement in order to lower the risk probability, it does indicate which variable to manipulate, eliminating the need to change the entire job (Marras *et al*., 1999).

Of the two variables that yielded the greatest individual odds ratio, maximum moment is included in the model, but sagittal velocity is not. Marras *et al*. point out that this is not of great concern; due to the high degree of correlation between factors, Sagittal

Table 1. Marras *et al*. 1993 Job Risk Classification Model

Variable	**Coefficient**	**SE**
Constant	-3.80	0.67
Lift Rate	0.0014	0.0006
Average Twisting Velocity	0.061	0.041
Maximum Moment	0.024	0.004
Maximum Sagittal Flexion	0.020	0.012
Maximum Lateral Velocity	0.036	0.014
Estimated Odds Ratio	10.7	
Confidence Interval	4.9-23.6	

velocity could very well be represented through its correlation with factors that were included in the model (Marras *et al*., 1993). The predictive power of the multiple logistic regression model relies on the interaction of the variables selected, in that individually, these variables are unable to reliably distinguish between high-risk and not high-risk (Marras *et al*., 1999).

Constructing our own multiple logistic regression model for this experiment was not feasible for two reasons; first, this study did not examine enough tasks to adequately establish a trend of multiple high-risk or multiple not high-risk tasks, and second, choosing a model is an iterative process that inevitably results in the inclusion of variables of the designers choosing. While the primary indicator of a good multiple logistic regression model is the odds ratio, the researcher may choose to "trade-off" a higher odds ratio in order to include a certain variable of interest.

The Marras model is highly predictive, and upon comparison with current lifting guides, was found to improve predictability two- or three-fold (Marras *et al*., 1993). Examination of like tasks using the NIOSH Lifting Equation yielded odds ratios as low as 3.5 (as compared to his 10.7). In addition to NIOSH findings, other studies have produced radically different results. These studies have typically identified psychosocial factors as significant variables in predicting occupational LBD risk, factors that Marras *et al*. chose to exclude. When compared to these other studies, Marras *et al*. identified the highly-repetitive nature of their tasks as the cause for the differing outcomes (Marras *et al*., 1993).

In a 1992 study, Marras evaluated the accuracy and repeatability of the LMM as compared to a commercially available two-dimensional, video-based motion evaluation system and a three-dimensional reference frame (Marras, 1992). He found the LMM to yield position results slightly closer to the reference frame, but the velocity and accelerations of the LMM and motion analysis were roughly comparable (Marras, 1992).

He cited a number of limitations with the motion analysis system, including complicated set-up, high rates of occlusion due to "machinery, equipment, assembly lines, other workers, mist, poor lighting, etc", the inability to follow workers to alternate work stations, sampling rate limitations, time-consuming analyses, and prohibitive expense (Marras, 1992, Marras *et al*., 1999). But the motion analysis equipment used by Marras was just a frontrunner to the strides made by today's motion capture technology and may prove a viable alternative after all.

Motion Capture

Human motion capture equipment first came around in the late 1980's. These magnetic, optical, and inertial based systems were originally designed in cooperation with the military, but expanded to such applications as: animation and motion capture, medicine, biomechanics, virtual reality and visualization, simulation and training, and military helmet tracking (Ascension Technology Corporation, 2005). The three types of motion capture systems have one common goal—to translate human motion to a digital form and record the position and orientation of the human body in space. While magnetic systems benefit from low cost, limited markers, and no occlusion of data points, they suffer from interference from the environment. Inertial/mechanical systems are limited in scope and application. Optical systems, although faced with the physical occlusion mentioned previously and are limited by the number of subjects which can be successfully tracked simultaneously, are also immune to magnetic disturbances, are highly adjustable, sample at least as high as the LMM, and may be practical for industrial purposes. Compared with the archaic motion analysis used in the Marras *et al*. 1993 study, today's motion capture operates in three-dimensions, is far more affordable, and can typically account for occlusion given adequate preparation and layout time.

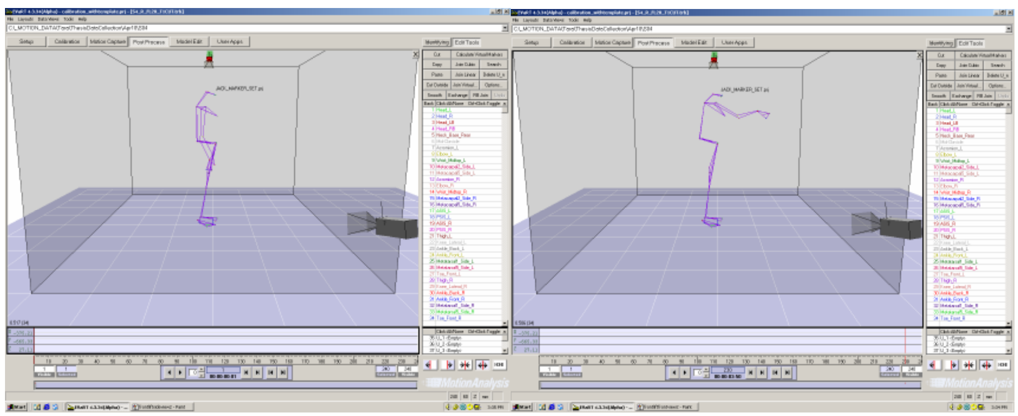
CHAPTER III

HYPOTHESIS AND METHODOLOGY

A variety of subjective measures were combined to assess risk factors for the 1993 Marras *et al*. study. Although a direct comparison to the LMM can not be fully validated, the goal of this study was to demonstrate a viable alternative for dynamic motion analysis as well as to demonstrate the multivariate nature of the Marras model, using slight variable manipulation to easily alter the RI of a particular task.

Study Design

This study examined six load transfer tasks using motion capture in the CAVS Human Systems Lab at MSU, of which, only two tasks will be reported here. Although research has shown vast differences in spinal loading and muscle activities for lifting tasks with variable load origins/destinations (i.e. pallet positioning, workstation height), the origin and destinations heights for this experiment did not vary between tasks, nor were they adjusted to accommodate each subject (Marras *et al*., 1999c). The first task consisted of a two-plane frontal lift in which a box with handles loaded to 21 pounds was lifted from a table at approximately waist height to a table of approximately chest height (See Figure 3). Load height at origin was 78 centimeters and 136 centimeters at destination. This task, even though it involves a greater load than task two, was chosen to compare to a low-risk task according to Marras *et al*. 1993's predictions about tasks consisting of movements contained primarily in two planes. Marras *et al*. found that while load weights and moments were typically lower for low-risk groups, box weight standard deviations were large compared to the means, indicating that the magnitude of spinal load may not necessarily discriminate well between low- and high-risk groups (1993). Additionally, Marras *et al.* found that conditions with larger loads required greater system stability, while the less taxing activities might actually contribute more to a trauma index (2004).

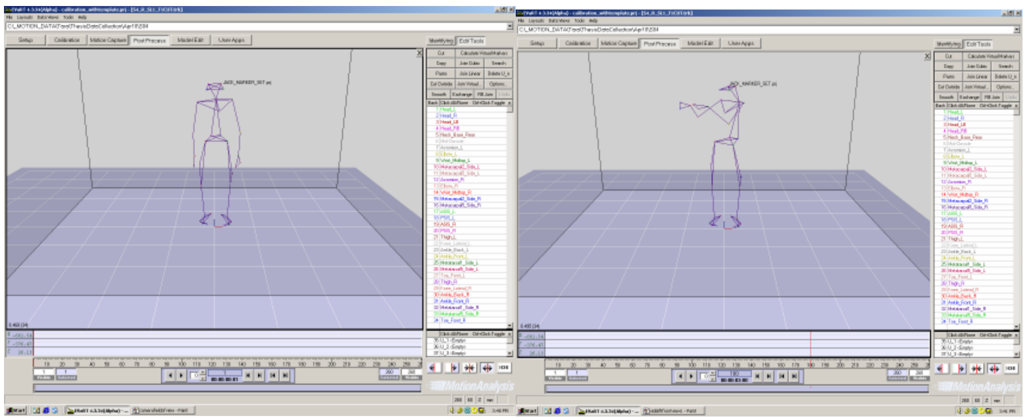


a) Origin of Lift b) Destination

Figure 3. Task 1. Front Lift*

*Although work surfaces are not represented here, tables were physical and not virtual in nature.

The second task consisted of lifting a box with handles weighing 1 pound at approximately waist height to a table of approximately chest height, situated 90 degrees to the right of the point of origin (See Figure 4). The subject was required to twist his or her body to complete the lift. The feet were stationary throughout. This task was chosen to represent a potentially high-risk task, as it involved movement in all three planes. Numerous studies have found that asymmetric lifting typically consisted of higher trunk velocities, decreased trunk strength, increased trunk muscle coactivation, and a reduction in max acceptable load, indicating a greater risk for LBD (as cited in Marras *et al*., 1993; Marras & Davis, 1998).



a) Origin of Lift b) Destination

Figure 4. Task 2. Side Lift*

*Although work surfaces are not represented here, tables were physical and not virtual in nature.

The experiment was conducted on thirty-six MSU volunteers who were financially compensated for their participation. All participants were required to complete an informed consent form which was approved by the Mississippi State University Institutional Review Board for research on human subjects and those with a history of recent musculoskeletal injury were eliminated from the study. There were 23 males and 13 females ranging in age from 19 to 48. The mean male standing height was 178.6 cm, while the mean female standing height was 164.3 cm. The means were representative of the 50th percentile standing height of North Americans, 179 cm and 164.3 cm for men and women, respectively. The range of standing height (152 cm – 192 cm) accounted for the 5th percentile female (154 cm) all the way up to the 95th percentile male (190 cm).

Research was conducted over a nine-day time period, with participation taking approximately 1 hour per subject. After a brief orientation, verbal confirmation of good musculoskeletal health, and granting of consent, the participant was fitted with the motion capture suit (see Figure 5).

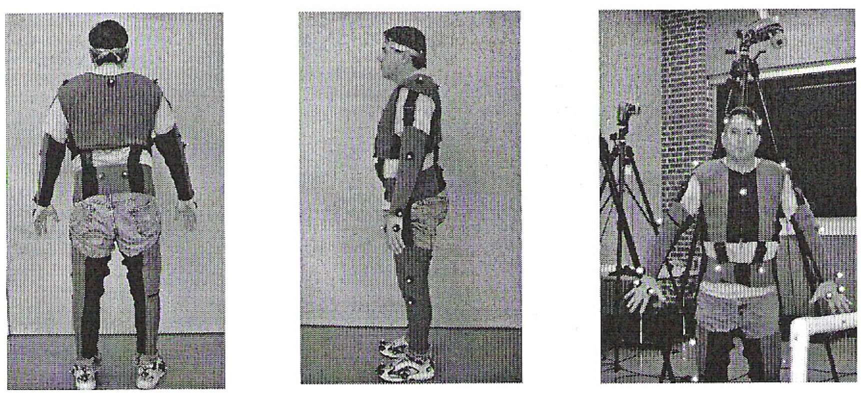


Figure 5. Motion Capture Suit

Markers were placed at designated locations based on system guidance for maximum coverage of the body's articulating points. Thirty-four markers in all were used (See Appendix A). Two trials of each task were performed and recorded. All extraneous motion was ignored.

The independent variables in this experiment were task asymmetry, individual anthropometric measurements, and individual musculoskeletal history. The dependent variables were 3-D trunk kinematic factors (angles, velocities, and accelerations in the sagittal, lateral, and twisting planes) and moment arms between the load and the L5/S1 vertebrae (Davis & Seol, 2005).

Calibration and Collection

Motion capture data was collected using the EVaRT 4.2 Eagle Digital System from the MotionAnalysis Corporation, California, sampled at 60 Hz. The EVaRT Motion Capture system is comprised of a number of infrared "Eagle" cameras. The system is designed to establish a relationship between real-world positions and corresponding image-coordinates from each camera. Image coordinates are picked up by the detection of small, spherical infrared reflectors placed at strategic points on the body (reference Appendix A). A 3-D position in space is defined by the intersection of optical rays and those positions are then mapped onto the computer software creating a real-time representation of the 34 markers which resemble a rough human shape on the monitor. The markers are then identified, or linked, by the computer software, turning a series of marker dots into a bare, skeletal-like portrayal of the human. Once the skeleton is linked, understanding the translation of human subject into digital human is simple and the data can be analyzed. There are a number of steps involved in achieving a successful motion capture which will be outlined in detail below.

The first step in a successful motion capture involves choosing a task or motion to be recorded and defining a *capture volume*. The capture volume should adequately accommodate the task to be performed without forcing any part of the body to move outside of the space. For this experiment, the capture volume was set at 3 meters wide (X-axis), 2 meters deep (Y-axis), and 2.5 meters high (Z-axis). The size of the space and the kind of movements the task requires will dictate the number of cameras required.

The EVaRT system can function with as few as 6 cameras and as many as 32. The smaller the capture volume, the fewer cameras required. Six cameras should have been sufficient for the capture volume used in this experiment, but with the anticipation of marker occlusion based on the tables from which and to which the loads were lifted, eight cameras were used to provide better coverage of the space. Figure 6 shows the actual placement of the eight cameras about the defined capture volume and gives an example of the field of view for one particular camera. Cameras can also be arranged in tiers in order to accommodate volumes of extreme height. Once the number of cameras is decided, they are oriented in such a way that they cover the maximum amount of volume possible. Our goal was to have each point in space perceived by at least two and not more than three of the cameras in order to decrease confusion in the system. Once satisfied with the camera coverage, the calibration process began.

Camera calibration is a two-step process. The first step, frame calibration, is based on the predetermined location of four retro-reflective markers permanently affixed to an L-shaped frame. The system knows the measurement between these markers, and allows the cameras to determine their exact position, to account for geometric distortion of camera lenses, and to accurately measure focal length. The second step is a wand calibration, which also works based on predetermined marker locations. The wand, in the shape of a "T" has three markers placed across the top bar of the T. By waving the wand up and down, right and left, and combing the volume along the X-, Y-, and Z-axes,the 3-D camera view picks up the location of the markers to further orient the cameras. With calibration complete, motion capture can begin. All motion capture equipment was available through CAVS at MSU and was authorized for use through the MSU Office of Regulatory Compliance.

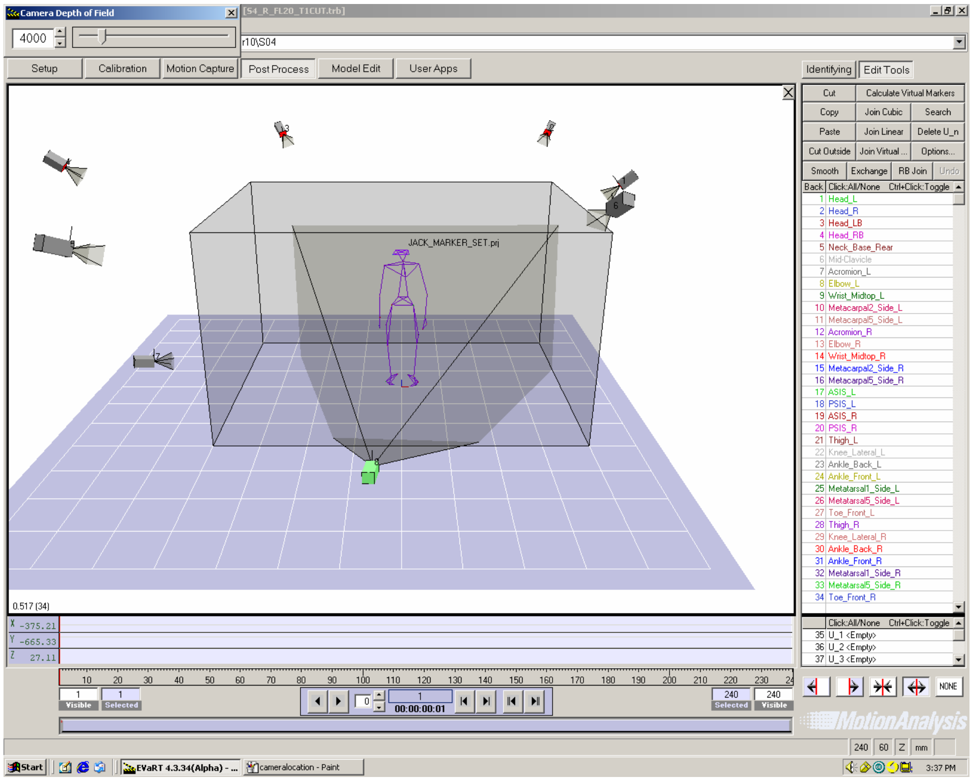


Figure 6. Camera Placement and Capture Volume

Data Processing

Each trial consisted of the time from when the box left the lower surface to when the box was placed on the upper surface, generally between 3 and 6 seconds, or 180 to 360 frames (60 frames per second). Following collection, it was necessary to clean the data, that is, remove any extraneous *ghost* markers that might mysteriously appear in the capture screen due to reflections off of shiny surfaces. Ghost markers need to be removed frame by frame, so fortunately because the collection was performed in a highly controlled setting, effort to accomplish this step was minimal. Next, two *virtual markers* were created. Virtual markers are points that can be added to the original collection to designate midpoints between two actual points. In this experiment, a "load" marker was created between the midpoints of the hands to designate the location of the downward vector of the box weight. Additionally, a marker was created between the feet in order to determine the angle of asymmetry between the mid-sagittal plane of the body and the location of the load (as defined by NIOSH) in order to perform the twisting calculations.

Data coordinates for designated markers were extracted from the motion capture software into an excel file. An example excel file for one trial is included at Appendix B. Position was calculated using simple geometry; the change in coordinates determined the lengths of sides of a triangle and the Pythagorean Theorem determined the third side. Basic trigonometry was used to calculate angles. Coordinates for the L5/S1 and load were used to calculate moment, mid-clavicle and base of the neck were used to calculate sagittal trunk motions, while right and left shoulder markers were used to calculate lateral trunk motions, and the angle coordinates for asymmetry (produced automatically by the MotionAnalysis software) were used to calculate angular positions/velocities/accelerations. The results were processed with a seven-point smoothing routine using normal distribution weighting to account for noise in the data. The smoothing protocol was performed once for position, twice more for velocity, and twice more for acceleration, in accordance with methods used by Marras *et al*., 1993. The smoothing was accomplished in Microsoft Excel using the NORMDIST function, which returns the normal cumulative distribution for a specified mean and standard deviation. The product of the NORMDIST function for each of the seven points divided by the sum of the same function for the same seven points yielded the smoothed data. Figure 7 graphically represents a sample result of the smoothed data for the Sagittal Extension/Flexion, Task 2.

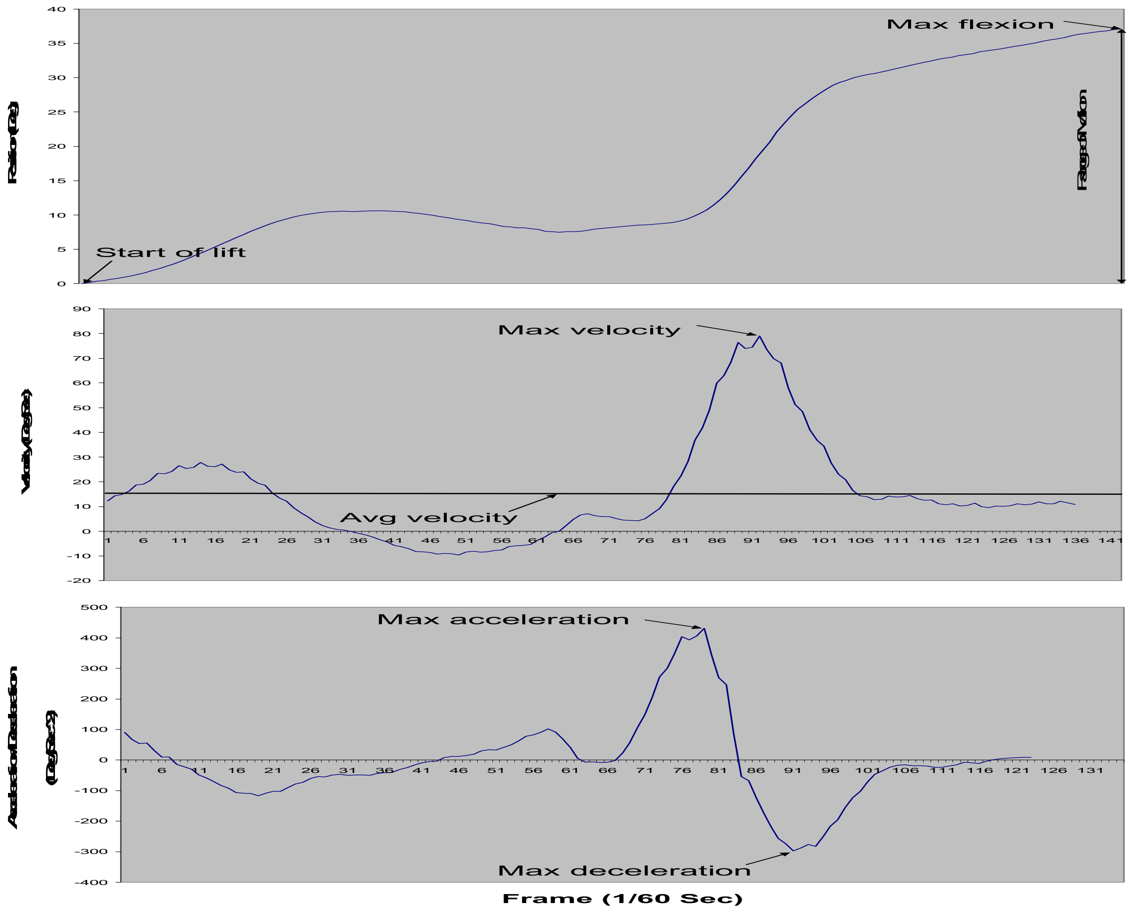


Figure 7. Sample Trunk Motion Characteristics using Smoothing Protocol

Potential confounding variables for this experiment included reflective surfaces inside the lab, camera positioning, capture volume coverage and calibration, number of cameras, marker displacement, camera settings, inaccurate health history disclosure, and insincere attempts for realistic motion.

CHAPTER IV

RESULTS

To determine statistically how our 2-plane and 3-plane tasks compared with those classified by Marras *et al.* (1993) as low-risk and high-risk, two sample t-tests were conducted to determine significant differences between our data and the Marras data, α = .05 (two-tailed). There were 36 subjects, each performing two trials. Additionally, a one-sample test on the mean differences between Task 1 and Task 2 was performed, again α = .05 (two-tailed). The descriptive statistics for Tasks 1 and 2 are shown in Table 2. The Marras *et al*. data (1993) that was used for comparison is included at Appendix E.

As mentioned previously, one of the advantages to using a multivariate model such as JRCM is the ability to manipulate variables to achieve a more desirable (i.e. lower) probability of high-risk group membership. The Marras *et al.* 1993 research examined tasks ranging from 6 to 1500 lifts per hour. For the sake of time in this experiment, only two repetitions per task were performed, and an arbitrary lift rate of 600 lifts was examined, based on a rough approximation of task duration (1 lift per 6 seconds → 10 lifts per minute → 600 lifts per hour) and close proximity to the midpoint of the Marras *et al*. 1993 range. Because lift rate was not controlled in this experiment, the arbitrary lift rate of 600 lifts per hour was compared to three others, 118.83 and 175.89 lifts per hour, the average lift rates for Marras *et al*. 1993's low- and high-risk

Table 2. Descriptive Statistics for Tasks 1 & 2, 95% Confidence Intervals

	2-Plane (n=36) vs. Low Risk (N=124)						3-Plane (n=36) vs. High Risk (N=111)						T. 1 vs. T.2 n=36	
Workplace Factors	Mean	SD	Min	Max	95% Conf. Int.		Mean	SD	Min	Max	95% Conf. Int.		95% C.I.	
Lift rate (lifts/hr)	600	0	600	600	451.41	510.93	600	0	600	600	422.50	425.72	0	0
Vertical load location at origin (m)	0.78	0	0.78	0.78	-0.32	-0.22	0.78	0	0.78	0.78	-0.26	-0.18	0	0
Vertical load location at destination (m)	1.36	0	1.36	1.36	0.16	0.26	1.36	0	1.36	1.36	0.28	0.36	0	0
Vertical distance traveled by load (m)	0.58	0	0.58	0.58	0.29	0.37	0.58	0	0.58	0.58	0.32	0.38	0	0
Average weight handled (N)	93.35	0	93.35	93.35	55.45	72.65	4.44	0	4.45	4.45	-95.06	-65.53	88.90	88.90
Maximum weight handled (N)	93.35	0	93.35	93.35	45.49	66.91	4.44	0	4.45	4.45	-116.44	-83.39	88.90	88.90
Average horizontal distance between load and L5/S1 (m)	0.51	0.06	0.39	0.67	-0.13	-0.07	0.48	0.08	0.05	0.62	-0.21	-0.15	0.01	0.05
Maximum horizontal distance between load and L5/S1 (m)	0.77	0.06	0.66	0.92	0.07	0.14	0.74	0.10	0.1	0.89	-0.06	0.02	0.01	0.06
Average moment (Nm)	47.76	5.15	36.69	62.36	24.76	35.49	2.13	0.36	0.24	2.74	-62.69	-43.56	44.09	47.16
Maximum moment (Nm)	72.34	5.42	61.52	85.97	41.61	55.64	3.29	0.43	0.44	3.93	-81.65	-59.08	67.38	70.72
Job satisfaction	This variable not measured													
Trunk Motion Factors														
Sagittal Plane														
Maximum extension position (degrees)	-9.07	5.85	-25.04	0	-1.48	3.46	-2.14	4.00	-29.33	0	4.19	8.13	-8.49	-5.36
Maximum flexion position (degrees)	20.49	11.03	0	60.68	5.70	14.61	26.87	10.41	0.74	55.83	4.51	13.52	-10.22	-2.53
Range of motion (degrees)	29.56	11.01	11.32	68.18	1.60	10.21	29.01	9.42	13.66	55.95	-6.64	1.67	-3.37	4.47
Average velocity (degrees/sec)	0.87	1.83	-6.72	6.44	-6.55	-4.77	7.01	3.61	-0.94	17.07	-6.64	-2.83	-7.34	-4.92
Maximum velocity (degrees/sec)	71.43	139.72	15.16	773.19	-12.59	77.96	61.08	56.26	17.21	342.75	-13.22	25.37	-25.72	46.43
Maximum acceleration (degrees/sec^2)	491.33	1138.28	71.23	6024.06	-107.09	635.02	303.53	392.59	61.02	2181.92	-145.62	119.22	-124.76	500.37
Maximum deceleration (degrees/sec^2)	-351.81	804.64	-5139.01	-69.11	-519.50	-17.14	-240.43	347.61	-1915.38	-43.54	-257.18	-38.77	-314.14	91.36
Lateral Plane														
Maximum left bend (degrees)	-2.20	2.74	-17.59	0	-0.79	1.56	-6.91	10.12	-49.64	0	-8.75	-2.14	1.51	7.91
Maximum right bend (degrees)	3.13	2.10	0.04	9.68	-11.33	-8.77	20.10	20.78	0	91.13	-2.07	11.07	-23.14	-10.80
Range of motion (degrees)	5.33	3.27	1.57	22.99	-18.27	-14.22	27.01	19.53	5.56	92.14	-3.65	8.80	-27.38	-15.98
Average velocity (degrees/sec)	0.23	0.65	-0.89	2.37	-7.49	-6.31	3.51	7.06	-14.62	31.65	-9.09	-4.46	-5.33	-1.22
Maximum velocity (degrees/sec)	10.41	7.09	3.17	56.50	-27.96	-22.11	46.59	38.28	2.86	190.01	-11.94	12.39	-47.42	-24.92
Maximum acceleration (degrees/sec^2)	82.77	87.31	26.82	766.63	-173.11	-120.42	225.59	171.91	53.84	1054.76	-135.33	-16.30	-193.50	-92.15
Maximum deceleration (degrees/sec^2)	-80.03	130.23	-1108.69	-18.43	-5.80	59.25	-227.00	170.16	-816.39	-42.28	-173.82	-72.87	90.44	203.48
Twisting Plane														
Maximum left twist (degrees)	-2.96	5.37	-44.54	0	-2.65	0.56	-1.97	1.83	-8.39	0	-4.94	-1.42	-2.30	0.32
Maximum right twist (degrees)	9.52	11.82	0.108	57.33	-4.97	2.46	83.10	5.78	66.28	96.04	66.78	71.51	-77.56	-69.60
Range of motion (degrees)	12.48	12.68	1.78	59.41	-8.51	-0.57	85.07	5.09	71.40	97.83	61.85	66.87	-76.64	-68.54
Average velocity (degrees/sec)	0.90	2.72	-7.17	10.49	-5.48	-3.62	21.47	4.75	8.45	32.60	10.87	14.66	-22.22	-18.92
Maximum velocity (degrees/sec)	36.74	41.47	6.06	203.94	-14.11	11.44	106.30	30.11	50.03	253.03	50.51	69.38	-84.25	-54.88
Maximum acceleration (degrees/sec^2)	301.84	345.21	50.98	1899.10	-76.96	141.09	408.55	328.93	130.85	2289.90	18.18	189.82	-234.14	20.72
Maximum deceleration (degrees/sec^2)	-216.05	206.17	-1070.68	-48.87	-177.90	-51.58	-268.75	158.51	-959.85	-72.76	-223.09	-137.37	-21.93	127.33

tasks respectively, and 1200 lifts per hour, double our established lift rate of 600 and nearing the maximum lift rate studied in Marras *et al*. 1993. By holding all other variables constant and manipulating the lift rate, it was possible to see how adjusting just one variable in the multiple logistic regression model affected the overall RI. Additional manipulation included examining each task with respective lift rate under two weight conditions, 1 pound and 21 pounds. Each combination was examined using the JRCM, the revised NIOSH Lifting Equation, and the Rapid Upper Limb Assessment.

Using the JRCM coefficients from Table 1 and the respective variable means from Table 2, the data collected in this experiment was applied to the Marras model to derive the RI. Example calculations for the two-plane front lift (Task 1) RI with 600 lifts per hour at 21 pounds are shown below:

Estimated logit for high-risk group membership:

$\hat{g}(x) = \beta_0+\beta_1x_1+\beta_2x_2+\beta_3x_3+\beta_4x_4+\beta_5x_5$

$\hat{g}(x) = -3.8+.0014x_1+.061x_2+.024x_3+.02x_4+.036x_5$

$\hat{g}(x) = -3.8+.0014(600)+.061(.903)+.024(72.335)+.02(20.487)+.036(10.413)$

$\hat{g}(x) = -.384$

Estimated logistic probability:

$\pi(x) = e^{\hat{g}(x)} / (1+e^{\hat{g}(x)})$

$\pi(x) = e^{-.384} / (1+e^{-.384})$

$\pi(x) = \mathbf{.405}$

The NIOSH Lifting Equation calculates an estimate of stress associated with manual lifting called the Lifting Index (LI). The LI is calculated by dividing the load weight by the Recommended Weight Limit (RWL), a value defined by the specific conditions of a task. The RWL is the product of six weighted variables: Load Constant (LC), Horizontal Multiplier (HM), Vertical Multiplier (VM), Distance Multiplier (DM), Asymmetric Multiplier (AM), Frequency Multiplier (FM), and Coupling Multiplier (CM) all of which can be calculated manually or extracted from NIOSH tables.

$$LI = \text{Load Weight} / RWL, \text{ where}$$

$$RWL = LC \times HM \times VM \times DM \times AM \times FM \times CM$$

Generally, a LI < 1 is considered desirable. See Appendix C for further clarification.

The RULA is a tool used to evaluate exposure to postures, muscle activities, and forces that could potentially lead to musculoskeletal disorders. RULA yields a Grand Score, with values of 1 or 2 being acceptable, 3 or 4 meriting further investigation of the task, 5 or 6 requiring change in the near future, and 7 or higher requiring immediate change. See Appendix D for further clarification. Results of the different manipulations applied to the JRCM, NIOSH, and RULA are shown in Table 3.

Based on the initial presumed lift rate of 600 lifts per hour, the calculated RI according to the Job Risk Classification Model was 41% for Task 1 and 66% for Task 2 (Table 3 in boldface), regardless of the difference in weight. In other words, the probability for the 2-plane front lift (Task 1) at 21 pounds to actually belong to the high risk group, was in fact, lower than the probability that the 3-plane side lift (Task 2) at 1 pound would belong to the high-risk group.

When examining the same scenario using NIOSH and RULA, the results were drastically different (also in boldface, Table 3). The LI was calculated as 7.16 for Task 1

Table 3. Risk Variable Manipulation

Job Risk Classification Model				
	Task 1 (2-plane lift)		**Task 2** (3-plane lift)	
Lift Rate	**1 lb**	**21 lbs**	**1 lb**	**21 lbs**
188.83	0.06	0.26	0.49	0.82
175.89	0.07	0.27	0.51	0.84
600	0.12	**0.41**	**0.66**	0.9
1200	0.23	0.61	0.82	0.96

NIOSH				
	Task 1 (2-plane lift)		**Task 2** (3-plane lift)	
Lift Rate	1 lb	21 lbs	1 lb	21 lbs
118.83	0.07	1.43	0.09	1.79
175.89	0.08	1.69	0.11	2.12
600	0.36	**7.16**	**0.44**	8.97
1200	not possible	not possible	not possible	not possible

RULA				
	Task 1 (2-plane lift)		**Task 2** (3-plane lift)	
Lift Rate	1 lb	21 lbs	1 lb	21 lbs
118.83	2	4	4	6
175.89	2	4	4	6
600	3	**6**	**4**	7
1200	3	6	4	7

and 0.44 for Task 2 (sample calculations at Appendix C) and therefore it would appear that Task 1 poses a substantially increased risk of lower back injury over Task 2. With the RULA, Task 1 received a Grand Score of 6, an indication that investigation and changes may be required as soon as possible, and Task 2 received a score of 4, which merits further investigation (sample calculations at Appendix D). Given these conflicting results, it was important to also examine the effects that changing the lift rate or load might have on the NIOSH and RULA outcomes. The NIOSH Lifting Index jumped drastically from the 175.89 lifts per minute scenario to the 600 lifts per minute scenario. This same tendency was consistent across all task/weight combinations. Additionally, the NIOSH Lifting Equation was unable to provide any LI at all at extremely high lift

rates due to a zero in the denominator of the LI equation. In certain scenarios, the RULA was unable to distinguish between different lift rates; the 3-plane, side lift scenario produced the same Grand Score for each lift rate.

CHAPTER V

DISCUSSION

Upon examination of statistical comparisons between Task 1 and the Marras *et al*. 1993 Low-Risk data as well as Task 2 and the Marras *et al*. 1993 High-Risk data, one might reasonably assume that the tasks don't adequately fall into these classifications. The two-plane Task 1 was significantly different from the Low-Risk data in all but the following variables: maximum sagittal velocity and acceleration, maximum left bend, maximum lateral deceleration, maximum left and right twist, and maximum twisting velocity and acceleration. The three-plane Task 2 was significantly different from the High-Risk data in all but the following variables: maximum horizontal distance, sagittal range of motion, maximum sagittal velocity and acceleration, maximum right bend, lateral range of motion, and maximum lateral velocity. But based on the fact that many of the dependent variables were not significantly different between the two-plane and three-plane tasks in this study and in the Marras *et al*. 1993 study, suggests that perhaps this is not an issue. Similar to the Marras *et al*. 1993 results, there was a lot of overlap between Task 1 and Task 2 when examining the means and standard deviations. While many of the mean differences between Task 1 and 2 variables were significantly different, Marras found the velocity trunk motion factors to be the only variables that were consistently different between groups in all planes (Marras *et al*., 1993). The one-sample test on the differences of the means produced the same results as Marras; average velocity was the only consistently different variable.

What is of primary concern is the Risk Index, and upon application to the JRCM, the two-plane Task 1 was, in fact, a lower-risk task while the three-plane Task 2 was higher risk. Based on Marras' parameters regarding risk-group membership, these results support the original assumptions that Task 1 would appear to have a lower probability of high-risk group membership (movement in two planes) while Task 2 appears to have a higher probability of high-risk group membership (asymmetrical movement in three planes). This also highlights Marras' *et al*. 1993's presumption that load may not be all that indicative of risk-group classification. In fact, upon closer examination of the Marras *et al*. 1993 data in Appendix E, that study measured tasks classified as low-risk with average loads as high as 280.92 N, or 63 pounds, compared to our 21 pounds.

The results of analysis using the JRCM were contradictory to results obtained from NIOSH and RULA. This suggests a few things; first, the fact that most MMH tasks do have a significant velocity and acceleration component indicates that lifting guides assuming slow and symmetric lifting or those that make broad and generic categorizations are inaccurate and inadequate, and second, no one analysis tool used alone is sufficient to evaluate a task. Rather, a more comprehensive approach is desired. The Revised NIOSH lifting equation was designed to account for asymmetrical lifting and less than ideal coupling conditions but it is still limited in application. In a 2002 study, Dempsey concluded that a fairly high percentage of MMH tasks in the US can not adequately be assessed using NIOSH (2002). RULA, designed primarily for "upper limb analysis" is more a predictor of upper extremity disorders and less a predictor of LBD. A Rapid Entire Body Assessment (REBA) is currently undergoing validation.

Both the NIOSH lifting equation and RULA place heavy emphasis on the load, a factor that Marras *et al*., 1993 found unable to make significant distinction between low- and high-risk group membership when examined alone. Other conditions which might not be adequately accounted for in one particular model (psychosocial factors, vibrational or thermal energy, prolonged sitting, one-handed lifting) may be accounted for in other models.

The inconsistent nature of workplace and trunk motion variables across job-risk classification levels makes a direct comparison between the LMM and motion capture a difficult task. Both methods have shown the capability to collect similar types of data. The information in Table 4 shows a side-by side comparison of some of the different capabilities and limitations for each technology. The two technologies are capable of collecting virtually the same data. The motion capture system, obviously higher in price, would probably be the wiser choice given plans for a broader application of the system outside of lower back analyses.

The data required to run the Job Risk Classification Model and to input into NIOSH and RULA was easily recorded using motion capture. Ambrose, *et al.* used motion capture linked with the lower back analysis feature of Jack simulation software in order to predict spinal joint loads including compression and shear forces (2004). Exporting data coordinates out of the MotionAnalysis software into excel isn't difficult, but could be made even easier through an interface with Jack's task analysis toolkit

Table 4. LMM vs. Optical Motion Capture

	Lumbar Motion Monitor	Motion Capture
Cost	<<$150k, contract evaluations available	$150k system purchase, contract evaluations
Required Equipment	LMM, harness, computer, telemetry device, tape measure	Eagle camera system (Cameras, mounting hardware/tripods, wires), reflective markers,
Collection Frequency	60 Hz	60 Hz
Adjustability	Sizes large and small	Adjustable to all sizes
Range	Moves with subject to various work spaces	Confined to one work space at a time
Environment	all, except perhaps those exposed to the elements	all, except those with high surface reflection and minimal set-up time (direct
Application	lower back only	whole body
	unable to measure body position in relation to stationary work surfaces	able to measure body position in relation to stationary objects such as
Timeliness of Feedback	early, for easy intervention	early, for easy intervention

which outputs data directly into formatted excel files, eliminating one step from the data processing steps described in the methods section.

Current lifting guidelines don't adequately cover occupational tasks that involve kneeling, stooping, crawling, or prone and supine conditions. To the researcher's knowledge, such tasks could be included in the Marras model (except sitting tasks) and observed using the LMM, provided the physical dimensions of the LMM were not prohibitive. Such positions have the potential of causing musculoskeletal injuries or disorders to parts of the body other than the lower back and require observation of whole body movement, a capability the LMM lacks. Motion capture technology has the capability not only to observe this data but to map it using 3-D coordinates in order to derive more precise measurements of distances and body angles.

Ergonomic Interventions

Whatever the method chosen for data collection, once a risk is identified there are a number of interventions that can be applied to decrease high-risk probability. Just like the LMM, motion capture can provide nearly immediate feedback on the implementation of such interventions and, if interfaced with digital human modeling software, can predict future interventions or redesigns even before implementation. Potential interventions to decrease risk probability include (by Job Risk Classification Model variable): *lift rate*: rearrange job tasks, rotate jobs, add employees, automate; *average twisting velocity*: place work in front of material handler, spread out congested work areas, raise working heights; *maximum moment*: reduce weight requirements, install material handling aids, evaluate the transfer locations; *maximum sagittal flexion*: raise the heights of loads placed near the floor, adjust working heights relative to an individuals standing height, train employees on proper lifting techniques, and *maximum lateral velocity*: conveniently locate or raise the work relative to the handler (Marras *et al*., 1999). Researchers can also consider the use of stabilization instruction (Webber & Kriellaars, 2004) or consult the risk reduction guidelines outlined by McGill: avoid a fully flexed or bent spine and rotate the trunk using the hips, choose a posture to minimize the reaction moment on low back so long as the spine is not fully flexed, allow time for the disc nucleus to "equilibrate" and ligaments to regain stiffness after prolonged flexion, avoid lifting shortly after rising from bed, prestress the system even during "light" tasks, avoid twisting, exploit the acceleration profile of the load, avoid prolonged sitting, consider the best rest break strategies (1999).

As mentioned previously, origin or destination height was not adjusted based on individual subject standing height although it could easily affect injury risk due to excessive bending as a result of poor item placement. Two interventions that are commonly found in MMH tasks are lift tables and lift aids. Lift tables, which can automatically adjust the height of the load based on the amount of weight remaining on a pallet or table, can significantly reduced the mean LBD incidence rate by 7.42 per 100 full time employees (Marras *et al*., 2000). Lift aids, such as pneumatic lift assist devices and hoists, also reduced the LBD rates by over six injuries per 100 full-time employees. Unfortunately, such lifting devices are often difficult to use and are often disregarded by the user because they tend to be cumbersome, but given appropriate use, lift tables and lift aids combined were found to reduce the risk of LBD by almost 35%.

Experimental Limitations

There are several potential limitations of this study which should be addressed. First, this experiment was performed in a laboratory setting. While every effort for realism was made, the mock-up design was simply an example of a potential work station. In an industrial setting, workers may be performing other tasks, introducing additional risk factors that may not be easily accounted for.

Second, each subject performed only two trials per task because the study was conducted on previously recorded data. It is important to limit the number of subjects and repetitions in order for the research to be cost effective. The smaller the observation time, the less disruption into work practices and productivity levels. Although research varies on the appropriate number of trials to observe in order to account for variability

(Marras *et al*. 1993 recommended 10 trials), Allread *et al*. set out to determine how many repetitions per subject were ideal to adequately describe the risk parameters in the Marras model specifically. The study concluded that gains in risk predictability beyond 3 subjects per task and 3 repetitions per subject were negligible (2000).

Third, sincere attempts at realistic motion could not be controlled. This study was performed by students in a laboratory, but in an actual work setting, factors such as psychological, psychosocial, physical workplace demands, personal factors and definition of recovery can influence a previously injured individual's return to work (Ferguson *et al.*, 2003). Ferguson et al. examined a technique for determining sincerity of effort--hoping to quantify injury severity and improvement due to treatment, as well as determine job demands that are compatible with one's ability based on their achieved recovery (2003). Such technology and evaluation is available commercially through companies such as BTE Technologies but was outside the scope of this project.

Fourth, realistic application of the motion capture system must be addressed. The very nature of the spine makes it difficult to isolate certain areas to measure flexion and/or extension. In this experiment, a degree of whole trunk flexion was used to quantify lumbar region flexion, and was unable to account for flexion in thoracic vertebrae. To this researcher's knowledge, the LMM does not possess this capability either, regardless of the fact that it only mirrors the lumbar region because the top harness that anchors the device to the body attaches to the upper torso. Additionally, there are environmental conditions in which the use of motion capture technology isn't reasonable. As Marras pointed out in his original research, job tasks that require significant movement outside a designated area will not benefit from motion capture because the system is only capable of recording a defined space. Conditions with large or numerous obstructions may not work well either due to marker occlusion. While typically this limitation can be overcome with additional camera coverage, it may not always be possible to record data in these locations. Finally, inadequate setup and calibration due to time constraints should cause a researcher to think twice before using motion capture.

It is important to note that in the initial plans for this experiment, preliminary research was conducted in an automobile assembly plant on an assembly line with very brief and infrequent pauses in production. In addition to the hundreds of shiny automobiles moving through the capture area, the space was surrounded by large metal machinery, metal beams, metal roof trusses, and reflective cautionary signage. Because the line down-time was so short, set-up and calibration time was abbreviated and had to take place several hours before the actual collection would occur. In the time between set-up and collection, cameras were disturbed and calibration was thrown off. The result of the poor set-up resulted in extremely noisy data.

While the normal and properly calibrated capture will only pick up the number of markers used on the subject (34 in this case), the inadequacy of the calibration in the preliminary research caused a capture upwards of 65 markers per frame, ghost markers that were actually surface reflections. To the naked eye, it is easy to pick out the actual markers that make up the skeleton, but the computer can not ignore these reflections and is unable to identify and link the skeleton until the extraneous markers have been eliminated. Erasing these ghost markers is an extremely tedious task that needs to be done frame by frame, sixty frames per second. Clean-up for a thirty-second task which was poorly calibrated can literally take weeks. When you multiply that time by 100+ subjects, poorly calibrated motion capture is extremely prohibitive.

Future Work

There is a variety of future work that would both expand and improve on this research. One area would involve the development of a model for two-person lifts, a technique frequently used by nurses' aides to transfer patients. Nurses' aides actually have a higher rate of workman's compensation claims (3.6) as compared to manual material handlers (3.4) (Marras *et al*., 1999b). Preliminary research indicated that sharing the lifting task didn't cut the compressive and shear forces in half as might be expected (in some instances, reductions in forces were nonexistent). There were also indications of preferred sides to perform the lift, perhaps attributed to differences in muscle cross-sectional area, muscle activity patterns, and trunk and hip kinematics (Marras *et al*., 1999b). Past studies found the cross-sectional areas of the erector spinae, external oblique, and internal oblique muscles were 10 to 14% smaller on the right side vs. left, while the rectus abdominus was 11% larger (as cited in Marras & Davis, 1998). Also of interest would be an examination of one-handed lifting which was found to result in greater sagittal flexion, higher lateral velocity and virtually equivalent compressive loads to two-handed lifting (as cited in Ferguson *et al*., 2002).

Examination of fatigue or previous injury on lower back pain or LBD would be beneficial. Both the Marras study and this study observed individuals performing highly repetitive tasks which might be performed continuously over an eight-hour work day.

They did not, however, observe those tasks over the entire eight-hour shift and therefore, can not account for fatigue. It's been shown that trunk kinematics and sagittal trunk moment decrease over a 5-hour work session (Davis & Marras, 2000). Caldwell *et al.* stated that with fatigue of the extensor muscles, the back may become subject to increased lumbar flexion (or sagittal flexion), potentially causing the soft tissue structures of the spine to come under increased stress, leading to increased risk of injury (2003). Similarly, those with lower back pain display different muscle recruitment patterns from those without (Marras *et al*., 2004). Because the normalized time of muscle activation was longer in prior LBD patients, they are exposed to increased spinal loading when performing the same task as a non-injured counterpart and would therefore be at greater risk for additional LBDs (Ferguson *et al*., 2004)

Finally, future efforts to validate motion capture for ergonomic analysis purposes should be conducted. Such validation could be accomplished in a similar fashion as utilized in the 1992 Marras LMM validation, which was based on the position deviation from an actual position as defined by a three-dimensional reference frame (Marras, 1992).

CHAPTER VI

CONCLUSION

There is no question of the significance that lower back disorders have in industry. As long as manual material handling tasks remain, back injuries will continue to abound. Through examination with ergonomic analyses and interventions, industry can work to reduce these injury rates. Older, more commonly used ergonomic analysis tools tend to discount the incorporation of inertial forces or diversified lifting techniques. Dr. William Marras *et al*. developed a Job Risk Classification Model to more thoroughly evaluate risk in certain job tasks (1993). His data was collected using the Lumbar Motion Monitor, the first device of its kind to shadow movements of the lower back. While the LMM is certainly a valuable tool, other technologies, such as motion capture, exist to record the same data.

This study examined the application of motion capture technology to evaluate two laboratory lifting tasks, one in two planes, the other in three and the comparison of this technology to Marras' Job Risk Classification Model using the LMM. The data coordinates for 34 joint markers were extracted from motion capture software and converted into positions, velocities, and accelerations in the three cardinal planes. Once converted, this data was easily applied to the JRCM, the NIOSH Lifting Guide, and the Rapid Upper Limb Assessment, just as the LMM data could be applied to all three. The resulting Risk Indices supported the initial assumption that movement in two planes is characteristic of low-risk tasks, while movement in three planes is indicative of higher-risk tasks.

Motion capture technology has earned a bad reputation for being too complicated and time consuming to implement in an actual industrial setting. While this experiment implemented the motion capture system in a laboratory environment, it is of the researcher's opinion that motion capture technology can be effectively used in the work place, given adequate preparation and set-up time. Just as there are situations in which the LMM is impractical (sitting postures, extremely tight spaces, evaluation of full body movements) there are also situations in which use of motion capture may not be ideal (tasks performed in highly reflective environments with inadequate time to "mask", and tasks performed in multiple work spaces). These are some of the same limitations originally cited by Marras, but should more practically be referred to as guidelines for application and not limitations at all. Obviously, there are no "one-size-fits-all" evaluations for every work condition but the advantages and applications of motion capture far outweigh the negatives.

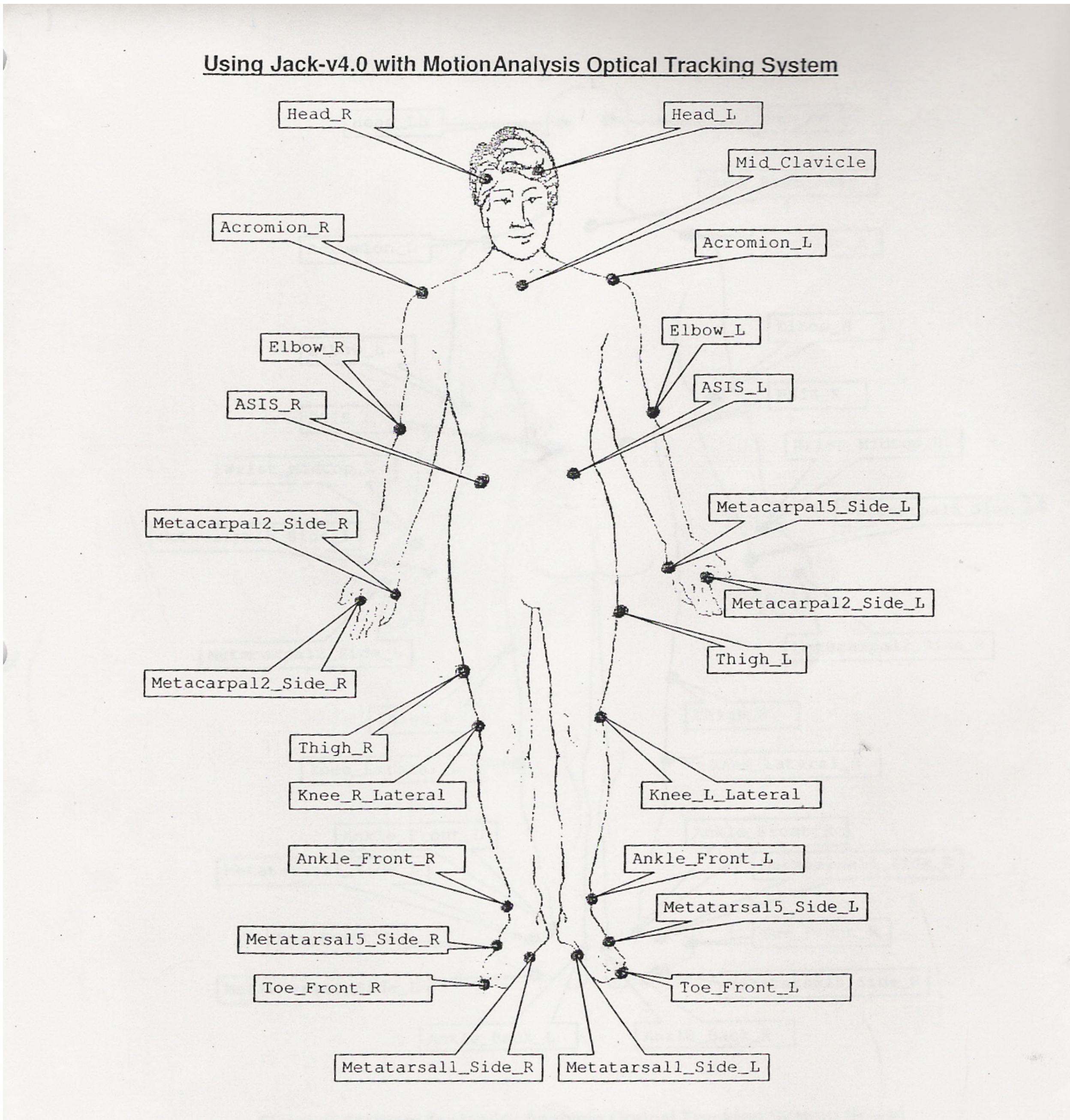
As the Marras *et al*. 1993 research has indicated, LBD risk is a multivariate issue; but use of the LMM limits the variable selection to those pertaining immediately to the trunk. In a study by Davis and Seol, kinematic changes in the lower back were present when another body region such as the feet or ankles had been injured (2005). Motion capture technology can provide an avenue for documenting such compensations and has the potential to generate its own multivariate model for ergonomic analysis that can incorporate whole body factors. Motion capture has other advantages too, such as profile- there is no bulky equipment to wear and it may be more comfortable and natural to wear than the LMM. Additionally, motion capture can be linked with digital human modeling and virtual reality software, and it can be applied not only to areas outside of ergonomics, but outside of MMH tasks as well, such as gait analyses, sports medicine applications, and prosthetic/orthotic development. Provided continued exploration, motion capture will prove to be a highly valued technology for all kinds of applications, all while returning manual material handlers to a safer, healthier work environment.

APPENDIX A

MOTION ANALYSIS MARKER PLACEMENT

A.1

Front View



A.2

Rear View

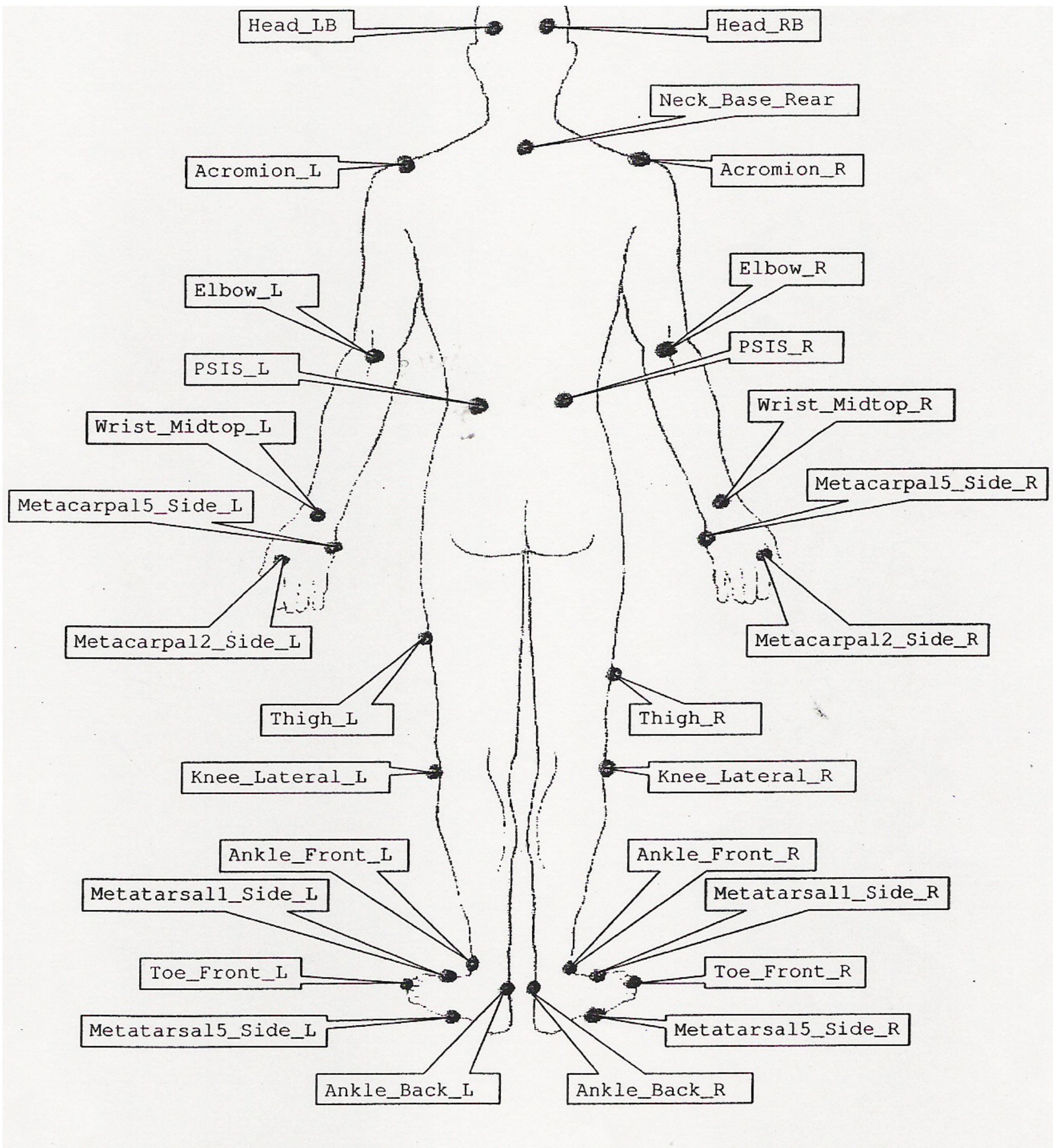


Figure 2. Markers for MotionAnalysis Optical Tracking System (Back)

A.3

Side View

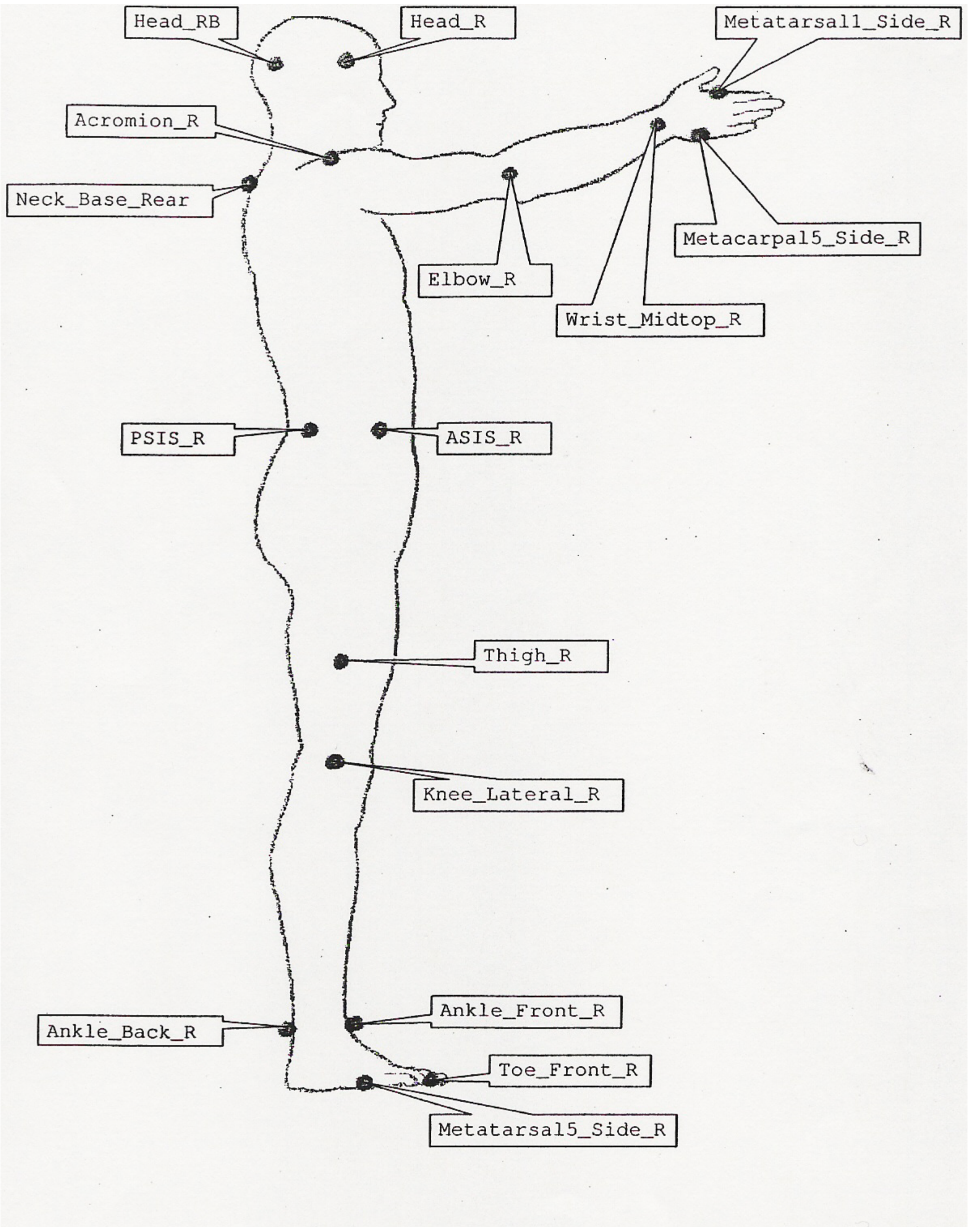


Figure 3. Markers for MotionAnalysis Optical Tracking System (Side)

APPENDIX B

MOTION CAPTURE COORDINATES

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DataRate	CameraRa	NumFram	Units		DataRate	CameraRa	NumFram	Units					
60	60	370	mm		60	60	370	mm					
Frame#	Time	V_L5			Frame#	Time	V_Load						
		X36	Y36	Z36			X37	Y37	Z37				
1	0	-1.30159	129.2803	1168.143	1	0	14.0534	-33.571	866.1522	0.163574			
2	0.017	-1.41442	129.2911	1168.095	2	0.017	13.84536	-33.4089	865.9518	0.163414			
3	0.033	-1.34165	129.2147	1168.128	3	0.033	13.91663	-33.3127	866.0085	0.163242			
4	0.05	-1.23319	129.1882	1168.142	4	0.05	13.95843	-33.2132	865.8284	0.16311	0.163206	0.000231	0.163221
5	0.067	-1.1385	129.1917	1168.168	5	0.067	13.96741	-33.2481	865.6079	0.163141	0.163149	0.000165	0.16315
6	0.083	-1.14851	129.3292	1168.162	6	0.083	13.57366	-32.8727	864.9166	0.162869	0.163112	0.000118	0.163158
7	0.1	-1.14727	129.2486	1168.049	7	0.1	12.5987	-33.2634	864.988	0.163092	0.163096	0.000104	0.163127
8	0.117	-1.05125	129.3359	1168.032	8	0.117	12.59721	-33.2693	864.8955	0.163177	0.163096	0.000104	0.163136
9	0.133	-0.99867	129.3526	1168.057	9	0.133	12.53025	-33.2407	864.7996	0.163155	0.163087	0.000102	0.163129
10	0.15	-1.04129	129.323	1167.969	10	0.15	12.57257	-33.2371	864.7331	0.163129	0.163131	3.92E-05	0.163129
11	0.167	-0.93614	129.2946	1167.96	11	0.167	12.78228	-33.2332	864.6632	0.163106	0.163131	3.89E-05	0.163126
12	0.183	-0.81806	129.2217	1167.833	12	0.183	14.38118	-33.1497	864.697	0.163081	0.163136	4.7E-05	0.163125
13	0.2	-0.68838	129.276	1167.721	13	0.2	14.56718	-33.1839	864.6155	0.163175	0.163125	5.08E-05	0.163116
14	0.217	-0.571	129.2583	1167.702	14	0.217	14.6055	-33.1278	864.4558	0.163094	0.16312	5.18E-05	0.163113
15	0.233	-0.64905	129.3454	1167.596	15	0.233	14.75072	-33.1375	864.3974	0.163211	0.163089	0.000102	0.163084
16	0.25	-0.59318	129.3621	1167.613	16	0.25	14.83046	-32.9833	864.4714	0.163076	0.163025	0.0002	0.163002
17	0.267	-0.41925	129.4634	1167.594	17	0.267	14.80689	-32.9209	864.5323	0.163097	0.162955	0.000224	0.162943
18	0.283	-0.41925	129.4634	1167.594	18	0.283	13.43994	-32.8341	864.1784	0.162888	0.162878	0.000258	0.162877
19	0.3	-0.38705	129.4837	1167.628	19	0.3	13.42386	-32.5655	863.9922	0.162637	0.16278	0.00024	0.162803
20	0.317	-0.38677	129.6264	1167.602	20	0.317	14.90398	-32.3342	864.1188	0.162681	0.162669	0.000259	0.16268
360	5.983	43.73381	71.20965	1181.664	360	5.983	-727.504	-117.562	1483.437	0.794004	0.794196	0.000238	0.79422
361	6	43.77694	71.06464	1181.672	361	6	-727.91	-116.998	1483.395	0.794273	0.794277	0.000329	0.794278
362	6.017	43.83476	70.7786	1181.774	362	6.017	-728.148	-116.731	1483.481	0.794429	0.794385	0.000404	0.794398
363	6.033	43.91883	70.49472	1181.854	363	6.033	-728.216	-116.603	1483.44	0.794479	0.79456	0.000368	0.794553
364	6.05	44.23069	70.21182	1182.006	364	6.05	-728.41	-116.125	1483.553	0.794792	0.794738	0.000355	0.794751
365	6.067	44.24728	69.91871	1182.036	365	6.067	-728.698	-115.728	1483.635	0.794927	0.794887	0.000346	0.79491
366	6.083	44.30098	69.72742	1181.987	366	6.083	-728.865	-115.389	1483.797	0.795019	0.795012	0.000309	0.795039
367	6.1	44.52295	69.5512	1182.143	367	6.1	-729.011	-115.006	1483.833	0.795246	0.795132	0.000217	0.795186
368	6.117	44.69607	69.25742	1182.105	368	6.117	-729.095	-114.533	1483.848	0.795318			
369	6.133	44.73281	68.98685	1182.136	369	6.133	-729.15	-114.343	1483.813	0.795302			
370	6.15	44.74316	68.76614	1182.045	370	6.15	-729.322	-113.888	1483.535	0.795324			

Average horizontal distance between load and L5/S1 (m)	0.445027
Maximum horizontal distance between load and L5/S1 (m)	0.795186

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DataRate	CameraRa	NumFram	Units			DataRate	CameraRa	NumFram	Units						
60	60	370	mm			60	60	370	mm						
Frame#	Time	Mid-Clavicle				Frame#	Time	Neck_Base_Rear							
		X6	Y6	Z6				X5	Y5	Z5					
1	0	79.42416	-33.9948	1510.271	1	0	1.88555	198.6219	1595.719	20.17002					
2	0.017	79.49549	-34.0941	1510.314	2	0.017	2.17302	198.5971	1595.983	20.21198					
3	0.033	79.52659	-34.2371	1510.282	3	0.033	2.12471	198.5239	1595.85	20.18471					
4	0.05	79.5776	-34.3789	1510.212	4	0.05	2.12471	198.5239	1595.85	20.18844	20.18591	0.01975	20.18392	4.62E-14	
5	0.067	79.71058	-34.4314	1510.189	5	0.067	2.17302	198.5971	1595.983	20.21206	20.18601	0.019656	20.18684	0.002928	
6	0.083	79.71045	-34.43	1510.19	6	0.083	2.16518	198.559	1595.752	20.16514	20.17023	0.034262	20.16804	-0.01587	
7	0.1	79.77979	-34.3847	1510.077	7	0.1	2.2055	198.5942	1595.654	20.16902	20.15929	0.040519	20.15615	-0.02776	20.1558
8	0.117	79.77401	-34.3366	1510.087	8	0.117	2.2055	198.5942	1595.654	20.17073	20.1484	0.041609	20.14785	-0.03607	20.14254
9	0.133	79.87302	-34.3266	1510.062	9	0.133	2.18599	198.8283	1595.392	20.10149	20.1301	0.036844	20.13438	-0.04954	20.12623
10	0.15	80.00765	-34.0658	1510.005	10	0.15	2.12623	198.8364	1595.273	20.10814	20.11189	0.046782	20.11341	-0.0705	20.11284
11	0.167	79.89542	-33.945	1510.031	11	0.167	2.12623	198.8364	1595.273	20.1122	20.09195	0.04811	20.09112	-0.09279	20.10137
12	0.183	79.92245	-33.7959	1509.961	12	0.183	2.03259	199.1003	1595.115	20.08395	20.07353	0.036101	20.07267	-0.11125	20.09029
13	0.2	79.93017	-33.7492	1509.949	13	0.2	2.14902	199.4332	1594.995	20.03771	20.07076	0.034298	20.0743	-0.10962	20.08108
14	0.217	80.07455	-33.5148	1509.816	14	0.217	2.38479	199.6518	1594.818	20.0294	20.06521	0.030131	20.07586	-0.10806	20.07623
15	0.233	80.07633	-33.3007	1509.837	15	0.233	2.38479	199.6518	1594.818	20.04181	20.06296	0.026399	20.07032	-0.1136	20.0762
16	0.25	80.05514	-32.8662	1509.711	16	0.25	2.55614	199.7809	1594.766	20.08212	20.06532	0.029183	20.06985	-0.11407	20.07978
17	0.267	80.04861	-32.7811	1509.622	17	0.267	2.61796	199.8766	1594.621	20.06924	20.07367	0.02831	20.07949	-0.10442	20.08401
18	0.283	80.04327	-32.6879	1509.618	18	0.283	2.63546	199.8567	1594.701	20.09648	20.0855	0.023657	20.09088	-0.09303	20.08921
19	0.3	80.04496	-32.6442	1509.615	19	0.3	2.63546	199.8567	1594.701	20.10048	20.09614	0.016348	20.09779	-0.08613	20.09691
20	0.317	80.33759	-32.685	1509.62	20	0.317	2.63546	199.8567	1594.701	20.09612	20.10552	0.024023	20.1039	-0.08002	20.10714
360	5.983	-150.722	-73.3105	1504.797	360	5.983	55.28308	27.21087	1626.537	50.45322	50.40634	0.160334	50.40634	30.22243	50.40797
361	6	-151.033	-73.4985	1504.906	361	6	55.22244	26.98944	1626.536	50.4371	50.501	0.197643	50.44445	30.26054	50.49216
362	6.017	-151.313	-73.7736	1504.904	362	6.017	55.17868	26.83498	1626.589	50.41616	50.5709	0.19231	50.5387	30.35478	50.56986
363	6.033	-151.563	-73.909	1504.961	363	6.033	55.21193	25.90822	1626.897	50.69621	50.63885	0.197698	50.66134	30.47742	50.64343
364	6.05	-151.694	-73.9997	1504.771	364	6.05	55.23341	25.38749	1626.829	50.84545	50.70012	0.197034	50.7712	30.58728	50.71869
365	6.067	-151.833	-74.2491	1505.006	365	6.067	55.22629	25.15747	1626.751	50.76788	50.78055	0.186398	50.81687	30.63295	
366	6.083	-151.947	-74.2342	1504.933	366	6.083	55.07001	24.91641	1626.746	50.85595	50.88762	0.154794	50.86511	30.68119	
367	6.1	-151.65	-74.5613	1504.831	367	6.1	55.09165	24.56885	1626.733	50.88208	50.97224	0.19049	50.9332	30.74929	
368	6.117	-151.86	-74.6993	1504.717	368	6.117	55.32522	23.97921	1626.575	51.00011					
369	6.133	-151.943	-74.7126	1504.671	369	6.133	55.36459	23.35506	1626.493	51.16569					
370	6.15	-151.943	-74.7126	1504.671	370	6.15	55.5033	22.99306	1626.578	51.28851					

Maximum sagittal extension (degrees)	-0.11407
Maximum sagittal flexion (degrees)	30.74929

20.1558	0.02653	20.15541											
20.14254	0.032623	20.14166											
20.12623	0.035221	20.12506											
20.11284	0.034488	20.1128	20.1167	0.025609	20.11747								
20.10137	0.030841	20.10326	20.10552	0.022823	20.10606	-0.67116							
20.09029	0.024673	20.09441	20.09577	0.019071	20.09616	-0.61919							
20.08108	0.015981	20.08428	20.08895	0.014941	20.08984	-0.37154							
20.07623	0.007357	20.07715	20.0846	0.010663	20.08624	-0.21168	-0.28561	0.285854	-0.25272				
20.0762	0.007276	20.07346	20.08266	0.007448	20.08469	-0.09712	-0.13571	0.322717	-0.145				
20.07978	0.010656	20.07732	20.08307	0.008255	20.0822	-0.14604	0.016167	0.307041	-0.02574				
20.08401	0.013587	20.08234	20.08607	0.011808	20.0842	0.117496	0.140383	0.299848	0.131649	0.136419	0.291491	0.136751	
20.08921	0.016582	20.08963	20.09143	0.015134	20.09025	0.378125	0.257458	0.299466	0.313277	0.256458	0.277195	0.285342	9.286925
20.09691	0.018723	20.09733	20.09897	0.017622	20.0978	0.443935	0.364194	0.284815	0.425766	0.367115	0.242686	0.404961	7.036444
20.10714	0.020894	20.10526	20.10785	0.020355	20.10626	0.497968	0.484977	0.198597	0.507708	0.464495	0.189765	0.495186	5.307321
50.40797	0.160897	50.40246	50.40906	0.164752	50.40496	4.441387							
50.49216	0.176315	50.47019	50.48983	0.172284	50.47931	4.373482							
50.56986	0.183315	50.55493											
50.64343	0.183773	50.65289											
50.71869	0.178297	50.74562											

Average sagittal velocity (degrees/sec)	5.19434	Maximum sagittal acceleration (degrees/sec^2)	119.216
Maximum sagittal velocity (degrees/sec)	38.1908	Maximum sagittal deceleration (degrees/sec^2)	-84.7039

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DataRate	CameraRa	NumFram	Units		
60	60	370	mm		
Frame#	Time	Acromion_R			
		X12	Y12	Z12	
1	0	-204.632	82.27307	1597.964	
2	0.017	-204.555	82.17737	1598.009	
3	0.033	-204.34	81.94689	1598.101	
4	0.05	-204.088	81.60152	1598.251	
5	0.067	-203.947	81.63203	1598.188	
6	0.083	-203.953	81.60231	1598.118	
7	0.1	-203.848	81.57354	1598.059	
8	0.117	-203.948	81.59947	1597.932	
9	0.133	-203.832	81.61775	1597.879	
10	0.15	-203.906	82.05092	1597.776	
11	0.167	-203.961	82.20963	1597.636	
12	0.183	-204.005	82.45496	1597.591	
13	0.2	-203.917	82.52848	1597.483	
14	0.217	-204.017	82.64381	1597.482	
15	0.233	-203.953	82.75613	1597.493	
16	0.25	-203.999	82.90481	1597.417	
17	0.267	-203.918	82.91557	1597.395	
18	0.283	-203.919	83.00901	1597.325	
19	0.3	-203.919	83.00901	1597.325	
20	0.317	-203.919	83.00901	1597.325	
360	5.983	-104.984	197.224	1636.293	
361	6	-105.087	196.9439	1636.218	
362	6.017	-105.022	196.487	1636.248	
363	6.033	-104.825	196.0384	1636.277	
364	6.05	-104.779	195.8875	1636.386	
365	6.067	-104.264	195.6486	1636.273	
366	6.083	-104.033	195.6247	1636.399	
367	6.1	-103.915	195.1261	1636.628	
368	6.117	-103.645	195.0936	1636.579	
369	6.133	-102.94	194.7423	1636.545	
370	6.15	-102.748	194.7406	1636.6	

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DataRate	CameraRa	NumFram	Units							
60	60	370	mm							
Frame#	Time	Acromion_L								
		X7	Y7	Z7						
1	0	215.5992	107.9084	1604.435		0.882202				
2	0.017	215.7161	107.8057	1604.37		0.867126				
3	0.033	215.7649	107.7403	1604.317		0.847746				
4	0.05	215.8386	107.6353	1604.274		0.821729	0.839414	0.026625	0.842809	0
5	0.067	215.9605	107.7505	1604.186		0.81827	0.829415	0.020261	0.833232	-0.00958
6	0.083	216.0721	107.7285	1604.099		0.815843	0.820501	0.013504	0.821831	-0.02098
7	0.1	216.1008	107.8593	1604.092		0.822984	0.814701	0.007009	0.814526	-0.02828
8	0.117	216.1072	108.0228	1603.886		0.812205	0.813669	0.006298	0.813582	-0.02923
9	0.133	216.0935	108.2088	1603.777		0.80473	0.809508	0.010779	0.808857	-0.03395
10	0.15	216.1482	108.4533	1603.693		0.807146	0.804616	0.01454	0.802658	-0.04015
11	0.167	216.1034	108.5857	1603.608		0.814503	0.795839	0.019349	0.794845	-0.04796
12	0.183	216.134	108.8609	1603.378		0.789142	0.78781	0.022783	0.787204	-0.05561
13	0.2	216.1163	109.0708	1603.213		0.781599	0.781752	0.023169	0.78221	-0.0606
14	0.217	216.0085	109.363	1603.065		0.761551	0.77607	0.020643	0.778972	-0.06384
15	0.233	216.0949	109.4553	1603.035		0.756	0.770624	0.012056	0.77493	-0.06788
16	0.25	216.1334	109.6531	1603.008		0.762323	0.769159	0.009853	0.772819	-0.06999
17	0.267	216.2104	109.8445	1603.022		0.767375	0.768516	0.009018	0.768291	-0.07452
18	0.283	216.1822	109.9934	1603.018		0.776379	0.770483	0.008742	0.77319	-0.06962
19	0.3	216.2107	109.946	1603.037		0.77889	0.773811	0.006441	0.776527	-0.06628
20	0.317	216.226	109.9846	1603.024		0.777097	0.774697	0.00482	0.775006	-0.0678
360	5.983	-28.6923	-189.147	1624.765		-8.59271	-8.50574	0.044765	-8.49171	-9.33451
361	6	-28.7549	-189.347	1624.799		-8.50832	-8.51429	0.046037	-8.50979	-9.3526
362	6.017	-29.1538	-189.651	1624.957		-8.46467	-8.52833	0.048128	-8.5234	-9.36621
363	6.033	-29.4182	-189.842	1625.039		-8.47681	-8.55098	0.078657	-8.55013	-9.39294
364	6.05	-29.5265	-190.051	1625.078		-8.54574	-8.62816	0.235376	-8.65773	-9.50054
365	6.067	-29.9587	-190.463	1625.067		-8.57644	-8.72704	0.310139	-8.7559	-9.59871
366	6.083	-30.0119	-190.522	1625.082		-8.69217	-8.88603	0.419298	-8.90375	-9.74656
367	6.1	-30.5969	-191.077	1624.841		-9.13299	-9.07249	0.491046	-9.07665	-9.91946
368	6.117	-30.6157	-191.423	1624.75		-9.20044				
369	6.133	-30.7589	-191.411	1624.365		-9.57765				
370	6.15	-30.9698	-191.931	1624.225		-9.78198				

Maximum left bend (degrees)	-10.3086
Maximum right bend (degrees)	1.677123

0.819642	0.014106	0.820684											
0.81279	0.012539	0.812915											
0.806215	0.012094	0.805799											
0.800555	0.012817	0.800235	0.80158	0.012483	0.801857								
0.795475	0.01339	0.795593	0.795793	0.011502	0.795876	-0.35184							
0.789954	0.012626	0.790447	0.790679	0.010538	0.790736	-0.32124							
0.784805	0.010857	0.785389	0.786353	0.009458	0.786563	-0.24548							
0.779896	0.00906	0.780175	0.782833	0.007884	0.783356	-0.18865	-0.21891	0.091817	-0.20517				
0.776802	0.006416	0.777117	0.779783	0.00604	0.780433	-0.18265	-0.1762	0.089183	-0.17218				
0.775277	0.00452	0.775513	0.777544	0.003982	0.778123	-0.13592	-0.13555	0.075906	-0.13713				
0.774248	0.003347	0.775598	0.776059	0.002027	0.776311	-0.10659	-0.10462	0.067271	-0.10306	-0.10931	0.065024	-0.10481	
0.773617	0.002652	0.77424	0.775244	0.000966	0.775465	-0.05283	-0.08266	0.05996	-0.06789	-0.08519	0.053895	-0.07533	1.842572
0.773629	0.002659	0.774773	0.774778	0.000646	0.774841	-0.03673	-0.05945	0.044164	-0.04487	-0.06568	0.040116	-0.05376	1.26915
0.773846	0.002643	0.774998	0.774381	0.000915	0.774349	-0.02895	-0.04399	0.029406	-0.03484	-0.05135	0.025645	-0.04187	0.698958
-8.52743	0.025084	-8.52136	-8.56629	0.042013	-8.56578	-0.69723							
-8.54029	0.054733	-8.54761	-8.58393	0.07258	-8.58982	-1.41426							
-8.57289	0.097355	-8.58361											
-8.62749	0.154289	-8.63733											
-8.71105	0.214967	-8.72195											

Average lateral velocity (degrees/sec)	-1.6068	Maximum lateral acceleration (degrees/sec^2)	78.17492
Maximum lateral velocity (degrees/sec)	5.246005	Maximum lateral deceleration (degrees/sec^2)	-54.1333

C:_MOTION_DATA\Tara\ThesisDataCollection\Apr13\S15\twist.ts

DataRate	CameraRa	NumFram	Units
60	60	370	mm

Frame#	Time	Angle1:Ankle_Front_R-Ankle_Front_L-Metacarpal2_Side_R-Metacarpal2_Side_L														
1	0	5.37655														
2	0.017	5.41692														
3	0.033	5.44298														
4	0.05	5.45406	5.492497	0.10083	5.478018	0										
5	0.067	5.52818	5.511181	0.086922	5.503317	0.0253										
6	0.083	5.67323	5.53311	0.078092	5.570295	0.092277										
7	0.1	5.55556	5.548033	0.067223	5.572765	0.094747	5.548793	0.041365	5.564789							
8	0.117	5.50734	5.559507	0.054079	5.579773	0.101755	5.561158	0.02719	5.569802							
9	0.133	5.57042	5.566426	0.052478	5.582843	0.104825	5.571144	0.009468	5.570727							
10	0.15	5.54744	5.553821	0.026923	5.554539	0.076522	5.572147	0.009732	5.575092	5.57028	0.005287	5.569431				
11	0.167	5.53438	5.558854	0.030374	5.564571	0.086553	5.573357	0.010329	5.577959	5.569944	0.005749	5.569781	0.02058			
12	0.183	5.57661	5.568349	0.020307	5.573218	0.095201	5.57008	0.011523	5.570717	5.568594	0.006802	5.568539	-0.07761			
13	0.2	5.585	5.569393	0.020617	5.577316	0.099298	5.564734	0.013178	5.562874	5.566375	0.008348	5.566848	-0.0995			
14	0.217	5.59079	5.573504	0.018242	5.581235	0.103217	5.562808	0.015666	5.56244	5.562105	0.010509	5.562125	-0.27785	-0.2229	0.174913	-0.21743
15	0.233	5.5738	5.564849	0.040588	5.556838	0.07882	5.559948	0.017056	5.560347	5.555537	0.013018	5.554668	-0.46601	-0.2632	0.138087	-0.21648
16	0.25	5.57773	5.552681	0.048474	5.545419	0.067402	5.553618	0.019375	5.555195	5.549212	0.015016	5.548411	-0.36806	-0.29645	0.111392	-0.24184
17	0.267	5.57622	5.543211	0.047575	5.541059	0.063041	5.544654	0.021029	5.545207	5.543613	0.016322	5.54345	-0.29185	-0.33492	0.071333	-0.31592
18	0.283	5.47379	5.53366	0.042914	5.544552	0.066534	5.53301	0.019936	5.531979	5.538204	0.015285	5.539265	-0.26154	-0.3366	0.069887	-0.31116
19	0.3	5.49144	5.517693	0.046161	5.528907	0.050889	5.526771	0.017973	5.526443	5.53242	0.012999	5.533989	-0.31036	-0.28155	0.097341	-0.31238
20	0.317	5.51871	5.507713	0.037815	5.514569	0.036551	5.522545	0.016253	5.523682	5.52685	0.009493	5.52772	-0.36878	-0.22704	0.138842	-0.27182
360	5.983	93.99447	93.99061	0.108547	93.9906	88.51259	94.01172	0.094418	93.99902	94.02579	0.088912	94.01066	1.939347			
361	6	94.0579	94.04543	0.125285	94.04225	88.56423	94.05823	0.121482	94.04703	94.07047	0.115718	94.05631	2.684864			
362	6.017	94.06364	94.11432	0.148955	94.09599	88.61797	94.11974	0.144288	94.10604							
363	6.033	94.1538	94.18662	0.165659	94.1666	88.68858	94.18943	0.162291	94.17635							
364	6.05	94.24047	94.26019	0.179857	94.25162	88.7736	94.26443	0.17584	94.25712							
365	6.067	94.36137	94.33687	0.193165	94.3465	88.86848										
366	6.083	94.43467	94.42713	0.191827	94.43242	88.95441										
367	6.1	94.50949	94.52261	0.199294	94.51561	89.03759										
368	6.117	94.59465														
369	6.133	94.69547														
370	6.15	94.82216														

Maximum left twist (degrees)	-0.54176	Average twisting velocity (degrees/sec)	15.13828	Maximum twisting acc	
Maximum right twist (degrees)	89.03759	Maximum twisting velocity (degrees/sec)	102.8208	Maximum twisting de	

APPENDIX C

NIOSH LIFTING GUIDE CALCULATIONS

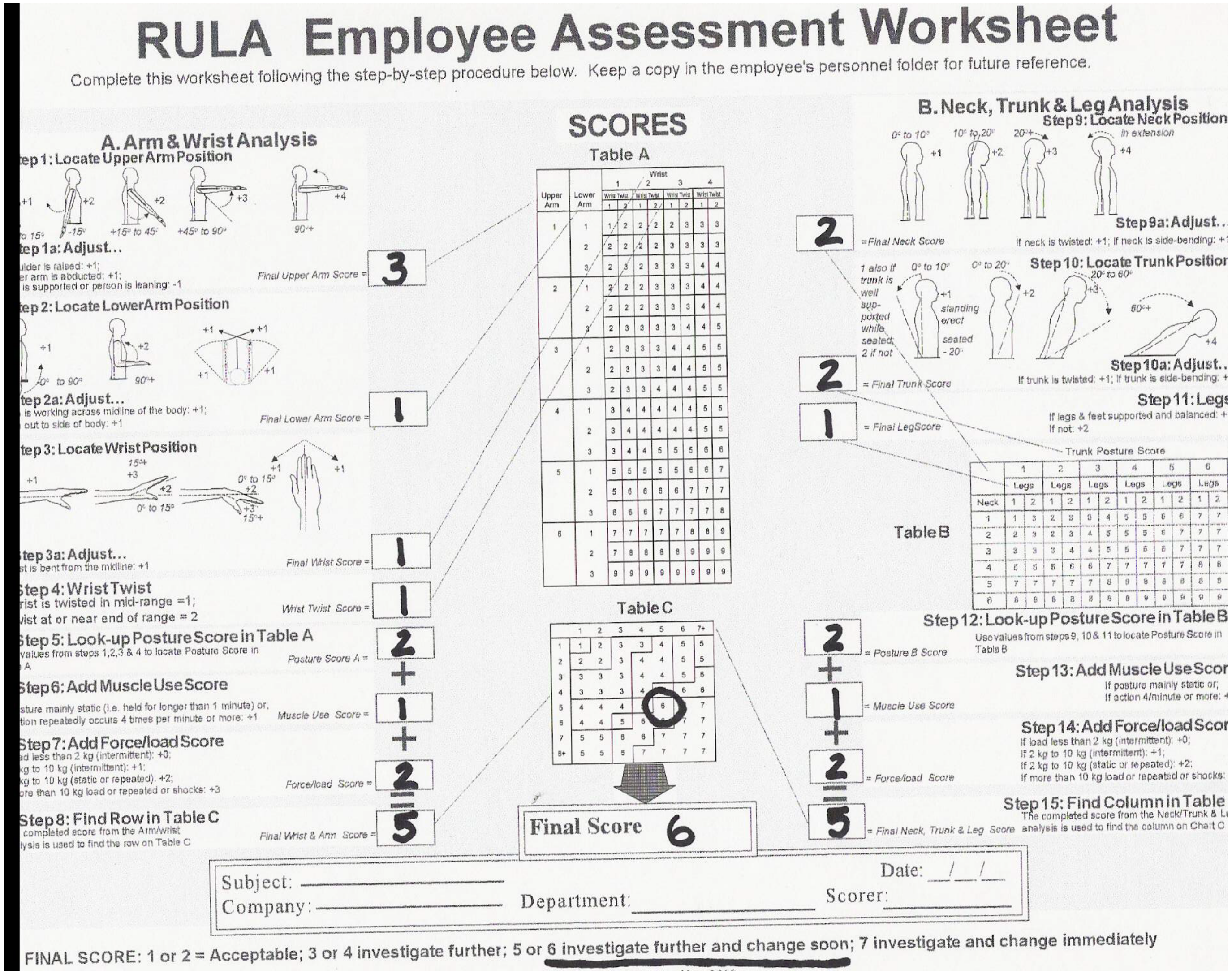
Task 1 Front Lift			
Factor	**Value**	**Formula**	**Multiplier**
Load Constant (kg)	Constant	LC=23	23
Horizontal Distance from midpoint of ankles (cm)	H=51	HM=25/H	0.49
Vertical height of hands (cm)	V=78	VM=1-(.003|V-75|)	0.99
Vertical Distance load is moved (cm)	D=58	DM=.82+(4.5/D)	0.9
Asymmetry (deg)	A=9.5	AM=1-(.0032A)	0.97
Frequency (lifts/minute)	F=10	FM=From NIOSH Table	0.13
Load Coupling (Good/Fair/Poor)	Good	CM=From NIOSH Table	1
Load Lifted (kg)	L=9.07		9.07
Recommended Weight Limit		RWL=LC x HM x VM x DM x AM x FM x CM	1.27
Lifting Index	LI=L/RWL		7.14

Task 2 Side Lift			
Factor	**Value**	**Formula**	**Multiplier**
Load Constant (kg)	Constant	LC=23	23
Horizontal Distance from midpoint of ankles (cm)	H=48	HM=25/H	0.52
Vertical height of hands (cm)	V=78	VM=1-(.003|V-75|)	0.99
Vertical Distance load is moved (cm)	D=58	DM=.82+(4.5/D)	0.9
Asymmetry (deg)	A=83	AM=1-(.0032A)	0.73
Frequency (lifts/minute)	F=10	FM=From NIOSH Table	0.13
Load Coupling (Good/Fair/Poor)	Good	CM=From NIOSH Table	1
Load Lifted (kg)	L=.45		0.45
Recommended Weight Limit		RWL=LC x HM x VM x DM x AM x FM x CM	1.01
Lifting Index	LI=L/RWL		0.45

APPENDIX D

RULA CALCULATIONS

D.1 (Task 1)



RULA Employee Assessment Worksheet

Complete this worksheet following the step-by-step procedure below. Keep a copy in the employee's personnel folder for future reference.

A. Arm & Wrist Analysis

ep 1: Locate Upper Arm Position

+1 +2 +2 +3 +4

o 15° -15° +15° to 45° +45° to 90° 90°+

ep 1a: Adjust...

ulder is raised: +1;
er arm is abducted: +1;
is supported or person is leaning: -1

Final Upper Arm Score = **3**

ep 2: Locate Lower Arm Position

+1 +2 +1 +1 +1 +1

0° to 90° 90°+

tep 2a: Adjust...

is working across midline of the body: +1;
out to side of body: +1

Final Lower Arm Score = **1**

tep 3: Locate Wrist Position

+1 15°+ +3 +2 0° to 15° +2 +3 15°+ +1 +1

0° to 15°

tep 3a: Adjust...

st is bent from the midline: +1

Final Wrist Score = **1**

tep 4: Wrist Twist

rist is twisted in mid-range =1;
ist at or near end of range = 2

Wrist Twist Score = **1**

tep 5: Look-up Posture Score in Table A

values from steps 1,2,3 & 4 to locate Posture Score in A

Posture Score A = **2**

+

tep 6: Add Muscle Use Score

sture mainly static (i.e. held for longer than 1 minute) or,
tion repeatedly occurs 4 times per minute or more: +1

Muscle Use Score = **1**

+

tep 7: Add Force/load Score

d less than 2 kg (intermittent): +0;
kg to 10 kg (intermittent): +1;
kg to 10 kg (static or repeated): +2;
re than 10 kg load or repeated or shocks: +3

Force/load Score = **2**

=

tep 8: Find Row in Table C

completed score from the Arm/wrist
lysis is used to find the row on Table C

Final Wrist & Arm Score = **5**

SCORES

Table A

Upper Arm	Lower Arm	Wrist 1, Wrist Twist 1	Wrist 1, Wrist Twist 2	Wrist 2, Wrist Twist 1	Wrist 2, Wrist Twist 2	Wrist 3, Wrist Twist 1	Wrist 3, Wrist Twist 2	Wrist 4, Wrist Twist 1	Wrist 4, Wrist Twist 2
1	1	1	2	2	2	2	3	3	3
	2	2	2	2	2	3	3	3	3
	3	2	3	2	3	3	3	4	4
2	1	2	2	2	3	3	3	4	4
	2	2	2	2	3	3	3	4	4
	3	2	3	3	3	3	4	4	5
3	1	2	3	3	3	4	4	5	5
	2	2	3	3	3	4	4	5	5
	3	2	3	3	4	4	4	5	5
4	1	3	4	4	4	4	4	5	5
	2	3	4	4	4	4	4	5	5
	3	3	4	4	5	5	5	6	6
5	1	5	5	5	5	5	6	6	7
	2	5	6	6	6	6	7	7	7
	3	6	6	6	7	7	7	7	8
6	1	7	7	7	7	7	8	8	9
	2	7	8	8	8	8	9	9	9
	3	9	9	9	9	9	9	9	9

Table C

	1	2	3	4	5	6	7+
1	1	2	3	3	4	5	5
2	2	2	3	4	4	5	5
3	3	3	3	4	4	5	6
4	3	3	3	4	5	6	6
5	4	4	4	5	6	[illegible]	7
6	4	4	5	6	6	7	7
7	5	5	6	6	7	7	7
8+	5	5	6	7	7	7	7

Final Score 6

B. Neck, Trunk & Leg Analysis

Step 9: Locate Neck Position

0° to 10° +1 10° to 20° +2 20°+ +3 in extension +4

Step 9a: Adjust...

If neck is twisted: +1; If neck is side-bending: +1

2 = Final Neck Score

Step 10: Locate Trunk Position

1 also if trunk is well sup-ported while seated 2 if not

0° to 10° +1 standing erect seated - 20° 0° to 20° +2 20° to 60° +3 60°+ +4

Step 10a: Adjust..

If trunk is twisted: +1; If trunk is side-bending: +

2 = Final Trunk Score

Step 11: Legs

If legs & feet supported and balanced: +
If not: +2

1 = Final Leg Score

Table B

Trunk Posture Score

Neck	1, Legs 1	1, Legs 2	2, Legs 1	2, Legs 2	3, Legs 1	3, Legs 2	4, Legs 1	4, Legs 2	5, Legs 1	5, Legs 2	6, Legs 1	6, Legs 2
1	1	3	2	3	3	4	5	5	6	6	7	7
2	2	3	2	3	4	5	5	5	6	7	7	7
3	3	3	3	4	4	5	5	6	6	7	7	7
4	5	5	5	6	6	7	7	7	7	7	8	8
5	7	7	7	7	7	8	8	8	8	8	8	8
6	8	8	8	8	8	8	8	9	9	9	9	9

Step 12: Look-up Posture Score in Table B

Use values from steps 9, 10 & 11 to locate Posture Score in Table B

2 = Posture B Score

+

Step 13: Add Muscle Use Scor

If posture mainly static or;
If action 4/minute or more: +

1 = Muscle Use Score

+

Step 14: Add Force/load Scor

If load less than 2 kg (intermittent): +0;
If 2 kg to 10 kg (intermittent): +1;
If 2 kg to 10 kg (static or repeated): +2;
If more than 10 kg load or repeated or shocks:

2 = Force/load Score

=

Step 15: Find Column in Table

The completed score from the Neck/Trunk & L
analysis is used to find the column on Chart C

5 = Final Neck, Trunk & Leg Score

Subject: ____________ Date: __/__/__
Company: ____________ Department: ____________ Scorer: ____________

FINAL SCORE: 1 or 2 = Acceptable; 3 or 4 investigate further; 5 or 6 investigate further and change soon; 7 investigate and change immediately

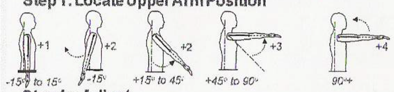
D.2 (Task 2)

RULA Employee Assessment Worksheet

Complete this worksheet following the step-by-step procedure below. Keep a copy in the employee's personnel folder for future reference.

A. Arm & Wrist Analysis

Step 1: Locate Upper Arm Position

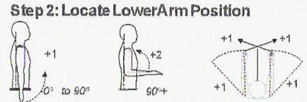


Step 1a: Adjust...

If shoulder is raised: +1;
If upper arm is abducted: +1;
If arm is supported or person is leaning: -1

Final Upper Arm Score = **3**

Step 2: Locate Lower Arm Position

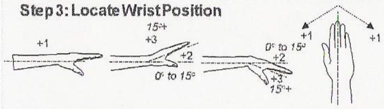


Step 2a: Adjust...

If arm is working across midline of the body: +1;
If arm out to side of body: +1

Final Lower Arm Score = **1**

Step 3: Locate Wrist Position



Step 3a: Adjust...

If wrist is bent from the midline: +1

Final Wrist Score = **1**

Step 4: Wrist Twist

If wrist is twisted in mid-range =1;
If twist at or near end of range = 2

Wrist Twist Score = **1**

Step 5: Look-up Posture Score in Table A

Use values from steps 1,2,3 & 4 to locate Posture Score in table A

Posture Score A = **2**

\+

Step 6: Add Muscle Use Score

If posture mainly static (i.e. held for longer than 1 minute) or,
If action repeatedly occurs 4 times per minute or more: +1

Muscle Use Score = **1**

\+

Step 7: Add Force/load Score

If load less than 2 kg (intermittent): +0;
If 2 kg to 10 kg (intermittent): +1;
If 2 kg to 10 kg (static or repeated): +2;
If more than 10 kg load or repeated or shocks: +3

Force/load Score = **0**

=

Step 8: Find Row in Table C

The completed score from the Arm/wrist analysis is used to find the row on Table C

Final Wrist & Arm Score = **3**

SCORES

Table A

Upper Arm	Lower Arm	Wrist 1, Wrist Twist 1	Wrist 1, Wrist Twist 2	Wrist 2, Wrist Twist 1	Wrist 2, Wrist Twist 2	Wrist 3, Wrist Twist 1	Wrist 3, Wrist Twist 2	Wrist 4, Wrist Twist 1	Wrist 4, Wrist Twist 2
1	1	1	2	2	2	2	3	3	3
	2	2	2	2	2	3	3	3	3
	3	2	3	2	3	3	3	4	4
2	1	2	2	2	3	3	3	4	4
	2	2	2	2	3	3	3	4	4
	3	2	3	3	3	3	4	4	5
3	1	2	3	3	3	4	4	5	5
	2	2	3	3	3	4	4	5	5
	3	2	3	3	4	4	4	5	5
4	1	3	4	4	4	4	4	5	5
	2	3	4	4	4	4	4	5	5
	3	3	4	4	5	5	5	6	6
5	1	5	5	5	5	5	6	6	7
	2	5	6	6	6	6	7	7	7
	3	6	6	6	7	7	7	7	8
6	1	7	7	7	7	7	8	8	9
	2	7	8	8	8	8	9	9	9
	3	9	9	9	9	9	9	9	9

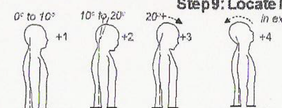
Table C

	1	2	3	4	5	6	7+
1	1	2	3	3	4	5	5
2	2	2	3	4	[illegible]	5	5
3	3	3	3	[illegible]	4	[illegible]	6
4	3	3	3	4	5	6	6
5	4	4	4	5	6	7	7
6	4	4	5	6	6	7	7
7	5	5	6	6	7	7	7
8+	5	5	6	7	7	7	7

Final Score 4

B. Neck, Trunk & Leg Analysis

Step 9: Locate Neck Position

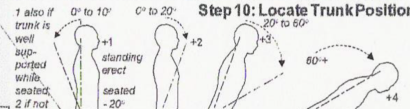


Step 9a: Adjust...

If neck is twisted: +1; If neck is side-bending: +1

2 = Final Neck Score

Step 10: Locate Trunk Position



Step 10a: Adjust...

If trunk is twisted: +1; If trunk is side-bending: +1

2+1 Final Trunk Score

Step 11: Legs

If legs & feet supported and balanced: +1;
If not: +2

1 = Final Leg Score

Table B

Trunk Posture Score

Neck	1, Legs 1	1, Legs 2	2, Legs 1	2, Legs 2	3, Legs 1	3, Legs 2	4, Legs 1	4, Legs 2	5, Legs 1	5, Legs 2	6, Legs 1	6, Legs 2
1	1	3	2	3	3	4	5	5	6	6	7	7
2	2	3	2	3	4	5	5	5	6	7	7	7
3	3	3	3	4	4	5	5	6	6	7	7	7
4	5	5	5	6	6	7	7	7	7	7	8	8
5	7	7	7	7	7	8	8	8	8	8	8	8
6	8	8	8	8	8	8	8	9	9	9	9	9

Step 12: Look-up Posture Score in Table B

Use values from steps 9, 10 & 11 to locate Posture Score in Table B

4 = Posture B Score

\+

Step 13: Add Muscle Use Score

If posture mainly static or;
If action 4/minute or more: +1

1 = Muscle Use Score

\+

Step 14: Add Force/load Score

If load less than 2 kg (intermittent): +0;
If 2 kg to 10 kg (intermittent): +1;
If 2 kg to 10 kg (static or repeated): +2;
If more than 10 kg load or repeated or shocks: +3

0 = Force/load Score

=

Step 15: Find Column in Table C

The completed score from the Neck/Trunk & Leg analysis is used to find the column on Chart C

5 = Final Neck, Trunk & Leg Score

Subject: ______________ Date: __/__/__
Company: ______________ Department: ______________ Scorer: ______________

FINAL SCORE: 1 or 2 = Acceptable; 3 or <u>4 investigate further</u>; 5 or 6 investigate further and change soon; 7 investigate and change immediately

APPENDIX E

MARRAS DATA

Workplace Factors								
	Marras Low Risk N=124				Marras High Risk N=111			
	Mean	SD	Min	Max	Mean	SD	Min	Max
Lift rate (lifts/hr)	118.83	169.09	5.4	1500	175.89	8.65	15.3	900
Vertical load location at origin (m)	1.05	0.27	0.18	2.18	1	0.21	0.38	1.8
Vertical load location at destination (m)	1.15	0.26	0.25	1.88	1.04	0.22	0.55	1.79
Vertical distance traveled by load (m)	0.25	0.22	0	1.04	0.23	0.17	0	0.76
Average weight handled (N)	29.3	48.87	0.45	280.92	84.74	79.39	0.45	423.61
Maximum weight handled (N)	37.15	60.83	0.45	325.51	104.36	88.81	0.45	423.61
Average horizontal distance between load and L5/S1 (m)	0.61	0.14	0.33	1.12	0.66	0.12	0.3	0.99
Maximum horizontal distance between load and L5/S1 (m)	0.67	0.19	0.33	1.17	0.76	0.17	0.38	1.24
Average moment (Nm)	17.7	29.18	0.17	150.72	55.26	51.41	0.16	258.23
Maximum moment (Nm)	23.64	38.62	0.17	198.21	73.65	60.65	0.19	275.9
Job satisfaction	7.28	1.95	1	10	5.96	2.26	1	10
Trunk Motion Factors								
Sagittal Plane								
Maximum extension position (degrees)	-10.19	10.58	-30	33.12	-8.3	9.1	-30.82	18.96
Maximum flexion position (degrees)	10.37	16.02	-25.23	45	17.85	16.61	-13.96	45
Range of motion (degrees)	23.82	14.22	3.99	67.74	31.5	15.67	7.5	75
Average velocity (degrees/sec)	6.55	4.28	1.4	35.73	11.74	8.14	3.27	48.88
Maximum velocity (degrees/sec)	38.69	26.52	9.02	193.29	55	38.23	14.2	207.55
Maximum acceleration (degrees/sec^2)	226.04	173.88	59.1	4120.1	316.73	224.57	80.61	1341.92
Maximum deceleration (degrees/sec^2)	-83.32	47.71	-227.12	-4.57	-92.45	63.55	-514.08	-18.45
Lateral Plane								
Maximum left bend (degrees)	-2.54	5.46	-23.8	13.96	-1.47	6.02	-16.8	24.49
Maximum right bend (degrees)	13.24	6.32	0.34	34.14	15.6	7.61	3.65	43.11
Range of motion (degrees)	21.59	10.34	5.42	62.41	24.44	9.77	7.1	47.54
Average velocity (degrees/sec)	7.15	3.16	2.13	18.86	10.28	4.54	3.12	33.11
Maximum velocity (degrees/sec)	35.45	12.88	11.97	76.25	46.36	19.12	13.51	119.94
Maximum acceleration (degrees/sec^2)	229.29	90.9	66.72	495.88	301.41	166.69	82.64	1030.29
Maximum deceleration (degrees/sec^2)	-106.2	58.27	-294.83	0	-103.65	60.31	-376.75	0
Twisting Plane								
Maximum left twist (degrees)	-1.92	5.36	-30	11.44	1.21	9.08	-27.56	29.54
Maximum right twist (degrees)	10.83	6.08	-11.2	30	13.95	8.69	-13.45	30
Range of motion (degrees)	17.08	8.13	1.74	38.59	20.71	10.61	3.28	53.3
Average velocity (degrees/sec)	5.44	3.19	0.66	17.44	8.71	6.61	1.02	34.77
Maximum velocity (degrees/sec)	38.04	17.51	5.93	91.97	46.36	25.61	8.06	136.72
Maximum acceleration (degrees/sec^2)	269.49	146.65	44.17	940.27	304.55	175.31	54.48	853.93
Maximum deceleration (degrees/sec^2)	-100.32	72.4	-325.93	-2.74	-88.52	70.3	-428.94	-5.84

(Marras et al., 1993)

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