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To cite this article: Thomas R. Waters , Vern Putz-Anderson & Sherry Baron (1998) Methods for Assessing the Physical Demands of Manual Lifting: A Review and Case Study from Warehousing, American Industrial Hygiene Association Journal, 59:12, 871-881, DOI: [10.1080/15428119891011045](https://doi.org/10.1080/15428119891011045)

To link to this article: <https://doi.org/10.1080/15428119891011045>



Published online: 18 Jun 2010.



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Methods for Assessing the Physical Demands of Manual Lifting: A Review and Case Study from Warehousing

Assessment of the physical demands of potentially hazardous manual material handling (MMH) activities is fundamental to the prevention of disabilities from occupationally related low back pain, a problem costing the nation billions of dollars annually. Although there is a variety of ergonomic assessment methods available for assessing MMH activities, there is a lack of practical information to assist users in choosing the most appropriate assessment methods for a particular job. This article reviews currently available assessment methods and presents case study results of a physically demanding repetitive manual lifting job in two grocery warehouses. The case study will provide a framework for a comparison of the methods and a discussion of relevant application issues designed to assist users in selecting appropriate methods for assessing MMH jobs. Based on the results of the study, it is concluded that all of the ergonomic methods were in agreement that the job of grocery selector has a high level of risk for low back pain. Differences between the methods were noted, however, that should be considered when choosing a specific method for a specific application.

Keywords: biomechanical, grocery warehouse, physiological, psychophysical

Injuries to the back are among the most common and significant musculoskeletal health problems facing society today, with occupationally related low back disorders (LBDs) being reported in epidemic proportions. In 1988 back disorders in the United States accounted for about one-fourth of all lost workdays (half a billion lost workdays) with 22 million cases reported that year.⁽¹⁾ The economic costs due to LBDs are staggering. A recent study placed the average cost of a worker's compensation claim for low back pain at \$8321, which was more than twice the average for all compensable claims combined (\$4075).⁽²⁾ It has been estimated that the total yearly cost of low back pain to society in 1990 was between 50 and 100 billion dollars.⁽³⁾ Moreover, as many as 30% of American workers are employed in jobs that routinely require them to perform activities that are associated with work-related back pain.⁽⁴⁾ These injuries have been linked to specific high-risk occupational activities that cause excessive biomechanical and physio-

logical loads on the worker's body, such as lifting, pushing, pulling, and carrying.⁽⁵⁾

Warehouse work is especially hazardous, requiring significant amounts of heavy, repetitive, manual lifting in less than optimal environments. It has been shown that the physiological demands of certain warehouse work exceeds the recommended limit for worker safety.⁽⁶⁾ Moreover, workers in these jobs typically lift while twisting, reaching, and bending sideways due to the design of the workplace. It is believed that excessive rotation or rapid movements at the low back during manual materials handling may significantly increase a worker's risk of developing an LBD. Specifically, results of several epidemiological studies indicate that repetitive twisting or lateral bending and lifting, even for relatively light loads, are significant risk factors for LBDs.⁽⁷⁻¹¹⁾

Warehousemen averaged nearly 10 back claims for workers' compensation per 100 workers during a given year.⁽¹²⁾ Moreover, the majority of back claims identify manual lifting as the

primary cause of injury.^(7,9,13) Unlike many occupational diseases, these disorders do not wait to appear when the worker is older, but occur most frequently in young and otherwise healthy workers. The average age of workers filing a compensation claim is 34 years, and workers often experience their first occurrence of minor low back pain in their early 20s.⁽¹²⁾

Fortunately, there is a tremendous opportunity for prevention of work-related back disorders in these high risk activities through ergonomic assessment and job redesign. Development of an effective redesign strategy, however, relies on accurate identification and quantification of the musculoskeletal stressors that are associated with increased risk of low back pain. Therefore, it is important to evaluate the various ergonomic assessment methods available so that practical evaluation of alternate designs is possible.

This article introduces a number of methods available for assessing manual material handling (MMH) jobs and presents a case study of an analysis of a physically demanding manual lifting activity in a dry grocery warehouse that will serve as an example for discussion purposes.

ASSESSMENT METHODS FOR MMH

A variety of assessment tools are available for the ergonomic evaluation of physically demanding manual lifting tasks. These tools range in complexity from simple checklists, which are designed to provide a general indication of the physical stress associated with a particular job, to complicated computer models that provide detailed information about specific risk factors. These tools provide objective information about the physical demands of manual handling tasks so that risk of injury can be estimated and an effective prevention strategy can be developed.

Choosing the most appropriate assessment method for a particular job may be difficult because each MMH job poses different combinations of biomechanical and physiological stresses on the worker. Different combinations of stresses require the use of different criteria to accurately assess MMH demands. For example, the biomechanical forces on the body limit how much weight or force is acceptable for infrequent heavy exertions, but it is the physiological demands on the worker that limit how much weight or force is appropriate when the job is moderately to highly repetitive. Jobs requiring moderate repetition rates, on the other hand, are probably best evaluated with psychophysical criteria. For this reason a variety of assessment tools have been developed that are based on biomechanics, psychophysics, and physiology. It is important to understand the differences between the assessment methods in order to choose the most appropriate tool for a particular analysis.

Methods based on biomechanical principles involve estimation or measurement of the kinematics of the system (position, velocity, and acceleration of the various body structures and objects) and estimation of the kinetics (external loads and muscle and joint reaction forces) required to obtain those kinematics. Biomechanical criteria are most appropriate for predicting maximum body forces for infrequent tasks. Static biomechanical modeling has been widely used to identify hazardous lifting tasks for many years. This approach has been questioned because it assumes that the mechanical system (i.e., the spine) is in static equilibrium, which is not generally true during a lifting task. If the lifting activity is relatively slow, however, then the loading estimate from a static model would be similar to the loading estimate that would be obtained from a dynamic biomechanical model. For certain tasks, such as those requiring high-speed movements, the static approach

would significantly underestimate the spinal loading associated with the activity and a dynamic assessment approach would be more appropriate.

Although biomechanical criteria limit what a worker can do on an intermittent or infrequent basis, physiological criteria are more important for repetitive activities that occur for extended periods of time (e.g., activity performed continuously for more than 15 minutes). Physiological criteria are concerned with the physiological demands of the job and how those demands compare with the physiological capacity of the person performing the activity. The goal of a physiological limit is to prevent local muscle or whole body fatigue. Local muscle fatigue can result from highly repetitive activity, where individual muscles or groups of muscles do not have an opportunity to recover between contractions, or from static muscular activities requiring heavy workloads, such as certain holding tasks or maintenance of awkward postures. In comparison, when the metabolic demands of dynamic and sustained activity exceed the energy-producing capacity of a worker, muscle contraction is affected and whole body fatigue is usually experienced.⁽¹⁴⁾

Measurement of oxygen consumption, heart rate, and prediction of energy expenditure provide the user with detailed information about the physiological demands of a job. Although this approach applies to a wide variety of tasks, such as lifting, pushing, pulling, and carrying, as well as for jobs with mixed tasks, it is limited to assessment of jobs with task elements with combined frequencies above about four to six per minute.

Psychophysical criteria have been developed for estimating the physical demands of manual lifting. Psychophysical criteria are based on studies of workers' perception of lifting capability, in which subjects are given control of the weight or frequency of the task, and other task variables such as the size of the load, height, distance, etc., are controlled by the experimenter. The subject then monitors his or her own feelings of exertion or fatigue, and adjusts the weight accordingly.

The assessment methods evaluated in this article include (1) the revised National Institute for Occupational Safety and Health (NIOSH) lifting equation (NLE); (2) the University of Michigan 3D Static Strength Prediction Program (3DSSPP); (3) the Oxylog portable oxygen consumption meter (VO₂); (4) the Polar portable heart rate monitor (HR); (5) the University of Michigan Energy Expenditure Prediction Program (EEPP); (6) the Chattanooga Corporation Lumbar Motion Monitor (LMM); (7) the Ohio State University risk assessment model (OSU); and, (8) the Snook and Ciriello⁽¹⁵⁾ psychophysical approach for assessing manual lifting demands.

NLE

The NLE is a mathematically based model for assessing the physical demands of two-handed manual lifting tasks.^(16,17) Input data for the NLE model include measurements of the location of the load relative to the worker, and the lifting frequency, duration, and other task-related factors. The principal results from the NLE are the recommended weight limit (RWL) and the Lifting Index (LI). The RWL is defined as the amount of weight that most workers should be able to lift safely for a specified lift without an increased risk of low back pain. The LI, which is defined as the ratio of actual weight lifted (*L*) to the recommended weight limit (i.e., $LI=L/RWL$), provides an index of the level of physical stress for a job. As the LI increases, the level of physical stress increases, and in theory the risk of injury increases. According to the NLE developers, it is likely that lifting tasks with an $LI>1.0$ pose an

increased risk for lifting-related low back pain for some fraction of the workforce and that many workers will be at elevated risk if the LI exceeds 3.0.⁽¹⁶⁾

3DSSPP

The 3DSSPP model is a computer program that provides estimates of static lumbar disc compression force and moments at the L5/S1 disc, as well as estimates of the muscle strength requirements needed to perform a specified material handling activity.⁽¹⁸⁾ Under one option the model requires input of 15 joint angles to define body posture, 3 anthropometric measures that define body characteristics, and 6 measurements that define the magnitude and direction of externally applied forces at the 2 hands. The model computes moments, axial disc compression force, antero-posterior and lateral shear forces, and specific muscle forces at the L5/S1 joint. The model also provides the resultant moment and strength capability of the male and female population for other major articulation joints. The estimated biomechanical loads can then be compared with baseline values that define various levels of physical stress or risk.

LMM and OSU Model

Studies have shown that excessive dynamic lumbar motion that may occur during a manual handling activity would significantly increase the biomechanical loading at the joints of the low back.⁽¹¹⁾ The LMM is a noninvasive mechanical spinal exoskeleton that is attached to the subject's hips and shoulders with a two-piece elastic restraint. The exoskeleton contains a set of lightweight electro-mechanical goniometers that measure the three-dimensional angular position of the low back of a subject engaged in a dynamic activity. These angular position measurements can be used to determine the sagittal, lateral, and transverse spine rotation angles, velocities, and accelerations.

In addition to the LMM, researchers at The Ohio State University have developed logistic regression models to estimate the probability that a certain task would be a member of a "high risk" LBD group.^(11,19) For the 1993 model, "high risk" was defined as jobs with at least 12 injuries per 200,000 hours of exposure.⁽¹¹⁾ For the 1995 model, "medium" and "high" risk categories were defined based upon a risk index that weights risk as a function of severity.⁽¹⁹⁾ Marras' models are based on five workplace and trunk motion variables that include (1) lift rate, (2) maximum moment, (3) maximum sagittal flexion, (4) average twisting velocity, and (5) maximum lateral velocity. To apply the models for a specific worker/task combination, the five workplace and trunk motion variables are measured and compared with a set of risk assessment benchmark scales that indicate increasing probability of occupationally related high-risk group membership. According to Marras et al.,⁽¹¹⁾ a scaled average of these variables should indicate a job's overall probability of high-risk group membership, because the five risk factors are scaled proportionally.

VO2 and HR

To characterize the physiological effects of MMH, a worker's heart rate and oxygen consumption is measured during the activity to determine the metabolic demands associated with heavy manual lifting. Oxygen consumption measurement provides a relatively objective assessment of the energy demands posed by the work load of the job, whereas heart rate is a measure of circulatory load. Measurement of heart rate, which is somewhat easier to obtain than oxygen consumption, may provide an indirect indication of metabolic load. Use of heart rate to predict energy expenditure,

however, is inherently less accurate than measurement of oxygen consumption, because factors not related to work can adversely affect heart rate.

University of Michigan EEPP

The EEPP provides a method for estimating the metabolic energy expenditure rate for a sequence of complex physical activities that is based on the physical characteristics of the job and the worker. The model is based on the assumption that a complex job can be broken down into a series of simple tasks (activity elements) that can be evaluated separately and then added together to determine the overall metabolic rate.⁽²⁰⁾ The model requires that data be collected about force, distance, frequency, posture, technique, gender, body weight, and time within each activity element. The model provides estimates of the incremental energy costs associated with each activity element as well as the average metabolic energy expenditure for a job over a selected time period.

Snook and Ciriello Psychophysical Database

Psychophysical criteria provide weight limits for lifting that are based on a worker's perception of the integration of the biomechanical and physiological demands of a job. Psychophysical databases of maximum acceptable weight limits for lifting have been developed from laboratory studies of workers' capabilities for a wide range of task conditions. In these studies, workers' maximum-acceptable-weight-of-lift for specified combinations of task characteristics are defined as the maximum amount of weight a person feels can be lifted repetitively, working as hard as possible without straining, or without becoming unusually tired, weakened, overheated, or out of breath. Typically, data are collected from a series of criterion tasks that are then used to generate normalized distributions of maximum weights that are acceptable to 10, 25, 50, 75, and 90% of the male and female population. Researchers have shown that back injuries increased for lifting tasks rated acceptable by fewer than 75 to 90% of the workers.^(7,21)

CASE STUDY

Methods

In response to concerns about the potential health hazard due to excessive manual lifting for grocery warehouse workers, assessments were carried out at two different grocery warehouses to evaluate the physical demands of the job of "grocery selector" or "order assembler." This job involves repetitive lifting of cases or bags of grocery items from supply pallets to an electrically driven pallet jack that moves along the aisles of the warehouse. The selection or "picking order" is dictated by a computer-generated list that contains the items and locations (aisle and slot numbers) for the order. An order typically consists of two full pallets stacked to a height of 70 to 90 inches. Both warehouses had recently begun phasing in a performance evaluation standard that required workers to complete orders within a specified time or face disciplinary action. In the first warehouse an incentive was given to workers for exceeding the performance standard. There was no incentive in the second warehouse.

In both settings, a variety of ergonomic assessment tools were used to evaluate the physical demands of the lifting job and a questionnaire was administered to selectors to determine their perceptions of physical workload and symptoms of musculoskeletal disorders. Additionally, Bureau of Labor Statistics Log of Occupational Injury and Illnesses (OSHA 200 logs) for the two

work sites were reviewed to determine the extent of recorded injuries and lost time due to injury for workers employed in these jobs. Previous reports have summarized the findings, conclusions, and recommendations for manual lifting in grocery warehouses obtained from these two studies.⁽²²⁻²⁵⁾ The objectives of this case study are (1) to provide data from a number of different ergonomic assessment tools for a physically demanding lifting activity that will be useful in discussing application issues regarding those tools, and (2) to discuss the potential impact the tool-dependent results may have on the development and implementation of an intervention.

Due to time constraints, slightly different combinations of assessment methods were used in the two warehouses to assess the job of grocery selector. In the first warehouse the job of grocery selector was analyzed with the revised NLE, the 3DSSPP, an Oxylog VO₂, a portable heart rate monitor, the EEPP, the Chattanooga LMM, and OSU model. In the second facility the job of order assembler was analyzed with the same tools as in the first study, with the exception that the 3DSSPP and EEPP methods were replaced with the Snook and Ciriello,⁽¹⁵⁾ psychophysical method for assessing manual lifting (SNOOK).

NLE

A total of 15 individual lifting tasks were analyzed with the NLE, 5 at the first warehouse and 10 at the second. The lifting tasks evaluated with the NLE were selectively chosen because they were judged by both workers and investigators as having a high potential for injury and they represented a diverse sample of stressful lifting postures. Input data for the NLE calculations for the lifting tasks at the first warehouse were collected at the work site while the worker was performing the lifts. Input data for the NLE calculations for the lifting tasks at the second warehouse were collected from laboratory simulations of lifts prerecorded on video tape at the work site. To compare LI values between tasks when the horizontal distance was greater than or equal to 25 inches, the horizontal distance was set equal to 25 inches for both warehouses. Finally, the magnitude of the frequency multiplier (FM) component of the RWL calculation for each of the five lifting tasks analyzed at the first warehouse was determined from the average lifting frequency observed at the work site (i.e., four lifts/min for 8 hours, or FM=0.45). The authors recognize that this approach may result in an overestimate of physical demand for the job. At the second warehouse, the magnitude of the FM value for the 10 lifting tasks was determined from the average lifting frequency observed for the lifting-cycle from which the respective lifting task was sampled. This approach also may result in an overestimate of the physical demand of the job.

3DSSPP

Five individual lifting tasks performed by two experienced male grocery selectors in Warehouse 1 were analyzed with the 3DSSPP computer program. Both of the workers, referred to subsequently as participants, were healthy and conditioned for work. Participant 1 was 35 years of age, 72 inches in height, and weighed 195 pounds. Participant 2 was 26 years of age, 69 inches in height, and weighed 155 pounds. Both participants were informed of the investigative procedures before data collection began. Participant 1 performed Tasks 1-4, and Participant 2 performed Task 5. Each participant was instructed to perform the lifts using the same technique he would use when actually selecting a grocery order.

For the five lifts selected for analysis, each participant was asked to momentarily hold his position at the lift-off point and set-down point. During the approximate 10 to 15-sec interval, the investi-

gator was able to record the angular values for each of 15 joints with the aid of an electro-goniometer (Lafayette Instruments, Inc., Model # 35, Lafayette, Ind.). The height, weight, and gender of the two workers and the angular position and force data serve as the input for the 3DSSPP biomechanical model. In addition to the measurements that were made at the work site, videotape and still photographs were made for each lift to assist the analyst in interpreting the measured joint angles for the analysis.

LMM/OSU

For this project, the LMM was used to collect three-dimensional trunk motion about the L5/S1 intervertebral joint for 389 individual lifts, 216 lifts at the first warehouse and 173 lifts at the second warehouse. The sagittal, lateral, and transverse rotation angles, velocity, and acceleration about the low back was measured as a function of time. Following data collection, the 389 lifts were classified as either low, medium, or high, depending on the vertical height of the hands at the origin or destination of the lift. A lift was categorized as low if either the starting or ending height of the hands was less than 30 inches from the floor; medium if the hand height was between 30 and 50 inches at both the start and end of the lift; and high for all remaining lifts.

The two OSU models were used to estimate the risk of high-risk group membership, by vertical lifting height category, for the 389 lifts evaluated with the LMM.

VO₂/HR

Six male grocery assemblers were randomly chosen for this phase of the investigation. All participants were informed of the procedures before the data were collected. For the testing trials a management representative selected the grocery orders for each assembler-participant. The order was judged to be of average size and difficulty. Each participant was fitted with an Oxylog VO₂⁽²⁶⁾ (Morgan Instruments, Inc., Andover, Mass.) and a portable HR (Polar USA Inc., Stamford, Conn.). Heart rate data were collected from a combination electrode-transmitter band that was worn on the chest and a watch-like receiver that was worn on the wrist. The receiver was able to store more than 8-hours of heart rate data for subsequent down-loading into a computer for analysis. The oxygen consumption values were automatically stored in a data logger attached to the oxygen consumption meter and later downloaded to a computer. The worker stood at rest in an erect posture for approximately 5 to 10 minutes before the grocery order was selected in order to allow the oxygen consumption and heart rate to stabilize to baseline conditions. Although it is impossible to control the actual work pace during a selection cycle, the three participants were asked to work as they normally would and to maintain a work pace approximately equivalent to 100% of the existing performance standard, to obtain a typical work sample.

A total of six individual lifting orders were analyzed with the Oxylog VO₂ (three in each study). The average evaluation time per lifting cycle was 32.8 minutes, and the total evaluation time was 197 minutes. In addition to measurement of the oxygen consumption and heart rate for each order, the workload (weight lifted per minute) was found by determining the total number of cases, total weight, and allowed time for each of the six orders.

To assist in the metabolic analysis, each of the six orders was videotaped, and a printout of the order showing the items to be selected was obtained from management. The printout listed the total number of items to be selected, as well as the weight and volume (size) of each item. The variables for this analysis included

(1) workload for each trip (average weight lifted per minute during the work cycle); (2) working heart rate (average heart rate during the work cycle); (3) working metabolic rate (average kcal per minute); (4) work pulse (difference between the resting and working heart rates).

EEEP

The videotapes that were made for the VO₂/HR analysis were used to estimate the energy expenditure requirements using the University of Michigan EEEP model. To simplify the assessment, randomly selected segments of the videotaped order selection sequences were analyzed using a frame-by-frame approach. Once the sequence was selected for analysis, each unique activity was categorized into one of seven task types that included lift/lower, walks, carry, hold, push/pull, handwork, or arm work. Then, task specific data were input into the program for each of the activities, such as heights and weights for lifting and pushing and pulling activities, distances traveled for walking or carrying activities, and duration of holding time, etc. The analyst then used the program to compute an estimate for the overall energy expenditure for the job, as well as task-specific energy expenditure estimates for each of the individual elements.

Snook and Ciriello

In the second warehouse the data obtained from the trunk motion and NLE components of the study were used to determine averages for the amount of weight lifted, horizontal location, lifting frequency, vertical displacement, and vertical height of lift for the 173 lifts discussed previously. These averages were then used to develop a table of weight limits for various percentages of males that would find these tasks acceptable based on the psychophysical database.⁽¹⁵⁾ According to Snook and Ciriello, the weight values in the database should be reduced 15% when handling boxes without handles and by approximately 50% when handling smaller boxes with extended horizontal reaching. The average weight handled for the 173 lifts was then compared with the psychophysical data for lifts with similar characteristics to determine the potential risk of back injury associated with the manual lifting.

OSHA Logs and Questionnaire

OSHA 200 logs were obtained from the two companies for periods between 1987 and 1992. These logs are the official report of occupational injuries and illnesses and are required by the Occupational Safety and Health Administration. Information from the logs was reviewed and rates of injuries and numbers of lost workdays were calculated for grocery assemblers.

A questionnaire was distributed to all grocery assemblers present on the day of the study at each site and was completed in a single group during work hours. The questionnaire included items that asked workers about the perceived physical workload of their jobs, symptoms of pain associated with musculoskeletal injuries, and whether they had experienced injuries during the previous year. Questions were also included concerning the overall workload and the workers' perceived control over their workload. A copy of the questionnaire and a more complete discussion of these indicators is provided elsewhere.^(22,25)

RESULTS

NLE

The results of the analysis of the 15 lifting tasks with the NLE are shown in Table I. The mean RWL for the 15 tasks was 6.2 lbs

TABLE I. Results of NLE Evaluation

Task #	Load (lbs)	RWL (lbs)	LI
1	30	7.2	4.2
2	38	6.8	5.6
3	42	5.2	8.1
4	38	5.2	7.3
5	58	7.2	8.0
6	39	5.2	7.8
7	40	5.0	7.7
8	27	5.6	4.8
9	60	6.6	9.1
10	29	4.5	6.4
11	22	4.7	4.7
12	44	6.9	6.4
13	28	10.4	2.7
14	27	6.3	4.3
15	35	6.2	5.7

and the LI values for the 15 tasks ranged between 2.7 and 9.1. Review of the intermediate calculations for the RWL revealed that the magnitude of the horizontal distances and lifting frequencies was primarily responsible for the low RWL values. On average, the combined effect of the horizontal distances and lifting frequencies accounted for about 81% of the reduction in the RWL from the starting weight of 51 lb. The developers of the NLE indicate that many workers will be at elevated risk of low back pain if they perform lifting tasks with LI values above 3.0.⁽¹⁶⁾

3DSSPP

The results of the analysis of the five lifting tasks using the University of Michigan 3DSSPP are shown in Table II. Four of the five tasks evaluated had a disc compression force greater than 770 pounds (3.4 kN), which is the NIOSH biomechanical criterion for limiting infrequent lifts. Based on disc compression alone, these four tasks would be considered unacceptable. The only lifting task with a disc compression value below 770 pounds was Task 4. From a strength perspective, only a fraction of the work force would have the strength capacity necessary to perform the five lifting tasks with the postures observed in this study. In fact, the model predicts that only 1% of the population would have the capability to perform Task 3, and only about 52% and 55% of the population would have the strength capability to perform Tasks 4 and 5, respectively.

Table II also provides data on shear force and torsion. Shear force is defined as the vector sum of the antero-posterior and

TABLE II. Results of 3DSSP Analysis

Task ^A #	Load Weight (lbs)	Disc Compression (lbs)	Min % ^B Capable (male)	Shear Force (lbs)	Torsion (ft-lbs)
1	30	930	63	123	69
2	38	830	70	131	113
3	42	896	1	116	40
4	38	662	52	87	61
5	58	801	55	112	68

^AThe five representative lifts were chosen to provide a range of stressful lifting postures. The conditions included (1) trunk flexion and no twist, (2) extended reach and small twist, (3) trunk flexion and high twist, (4) extended reach and high twist, and (5) shoulder high reach, moderate twist.

^BPercentage of population with sufficient strength capability.

TABLE III. Mean Peak Lumbar Trunk Kinematics, by Height Category (Warehouse 1)

	Rotation Angle ^A (degrees)			Rotation Velocity (degrees/sec)			Rotation Acceleration (degrees/sec ⁻²)		
	Sag	Lat	Tran	Sag	Lat	Tran	Sag	Lat	Tran
Low (<30 in.)	55.7	10.3	13.7	65.9	31.0	42.6	266.0	137.6	197.1
Med (30–50 in.)	37.5	11.3	15.6	51.8	33.3	46.2	225.2	151.6	209.7
High (>50 in.)	28.0	8.0	15.9	34.0	26.0	43.2	144.1	120.2	196.2

^AMaximum angular displacement from neutral posture.

lateral components of force applied perpendicular to the vertical axis of the spinal segment. As can be seen in Table II, there are significant shear forces for the five lifts evaluated in this study. These values are well below the acceptable limit of 200 lbs for lateral shear that has been proposed in the literature.⁽¹⁹⁾

Finally, spinal torsion is defined as the magnitude of the twisting moment about the vertical axis of the spinal segment. When a person twists to pick up a load, the musculoskeletal system must develop greater force on one side of the spine than on the other. These asymmetric muscular contractions between the right and left sides of the body create unbalanced asymmetric lateral forces as well as torsional moments on the spine. Research evidence suggests that increases in both shear force and spinal torsion, which accompany asymmetric loading, significantly increase the risk of LBDs, especially when heavy loads are lifted.^(27,28) For the present, there is insufficient data to predict the exact relationship between combinations of shear force and torsional levels and the risk of musculoskeletal injury. In general, asymmetric loading is associated with lower levels of acceptable lifting capacities and an increased risk of low back injury.^(29,30)

LMM and OSU Model

Trunk motions and workplace variables were recorded for 389 of the lifts that were performed by the 7 individuals who participated in the 2 warehouses. Of these 389 lifts, 55% were categorized as low lifts, 16% were categorized as medium lifts, and 29% were categorized as high lifts.

Trunk Motion and OSU Models

An example of the kinematic data collected with the LMM at Warehouse 1 is shown in Table III. Inspection of the table reveals that the sagittal rotation angles, velocities, and accelerations were greater for lifts classified as low compared with those classified as medium or high. From a biomechanical perspective, the spine would be exposed to significantly greater internal loading for these lifts than for lifts above 30 inches due to the increased dynamic loads and the requirement to lift a greater percentage of the upper body mass.

The results of the analysis of the 173 lifts analyzed with the 1993 OSU risk assessment model for Warehouse 2 are shown graphically in Figure 1. The horizontal bars indicate the individual contribution of risk associated with the individual factors, and the vertical arrows represent the overall probability of high-risk group membership for each of the height categories. Figures 2A and 2B provide a graphical summary of the results of the analysis for the two warehouses using the 1993 and 1995 OSU models. Note that the probability of high-risk group membership is consistently higher for the 1995 model than for the 1993 model.

Oxygen Consumption and Heart Rate

The results for oxygen consumption, heart rate, and workload assessment for the six participants are shown in Table IV. The results of an evaluation of the relationship between the various physiological measures using linear regression is shown in Table V. Working heart rate did not correlate well with either workload or working metabolic rate. There was a moderate positive correlation for

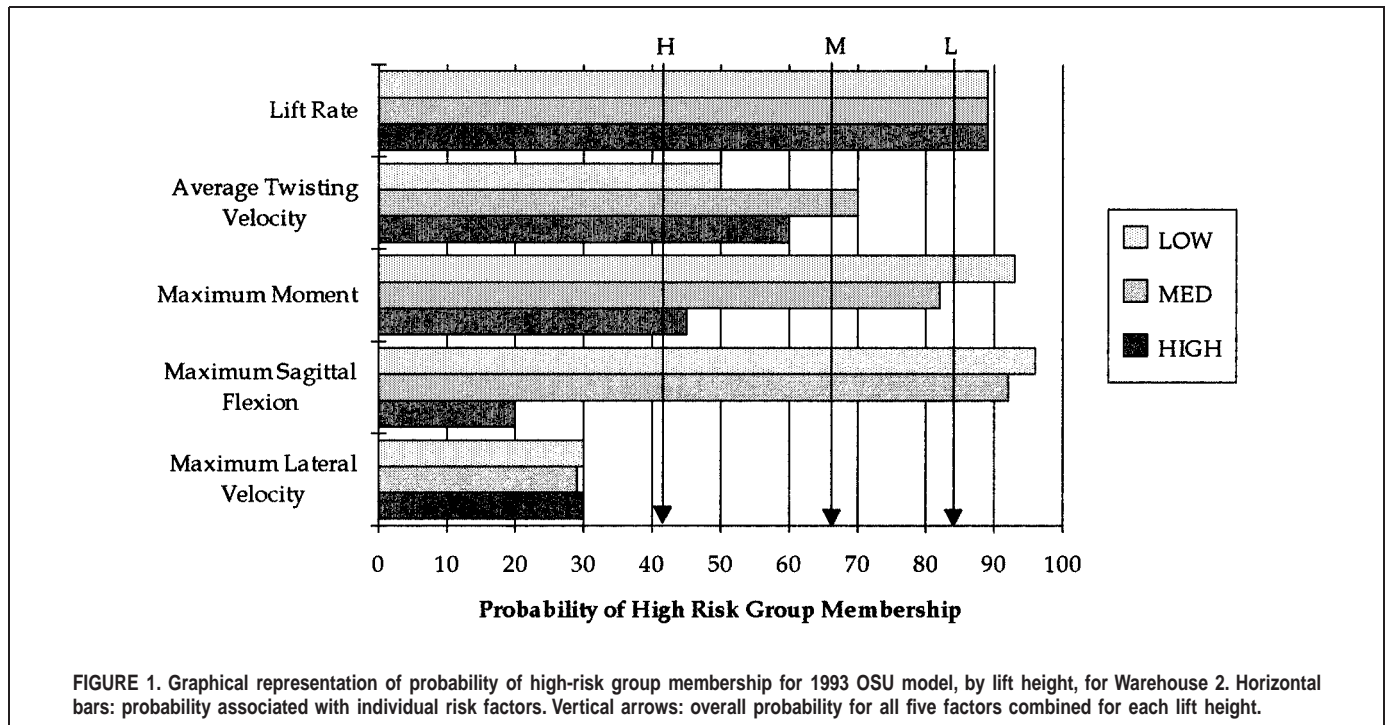


FIGURE 1. Graphical representation of probability of high-risk group membership for 1993 OSU model, by lift height, for Warehouse 2. Horizontal bars: probability associated with individual risk factors. Vertical arrows: overall probability for all five factors combined for each lift height.

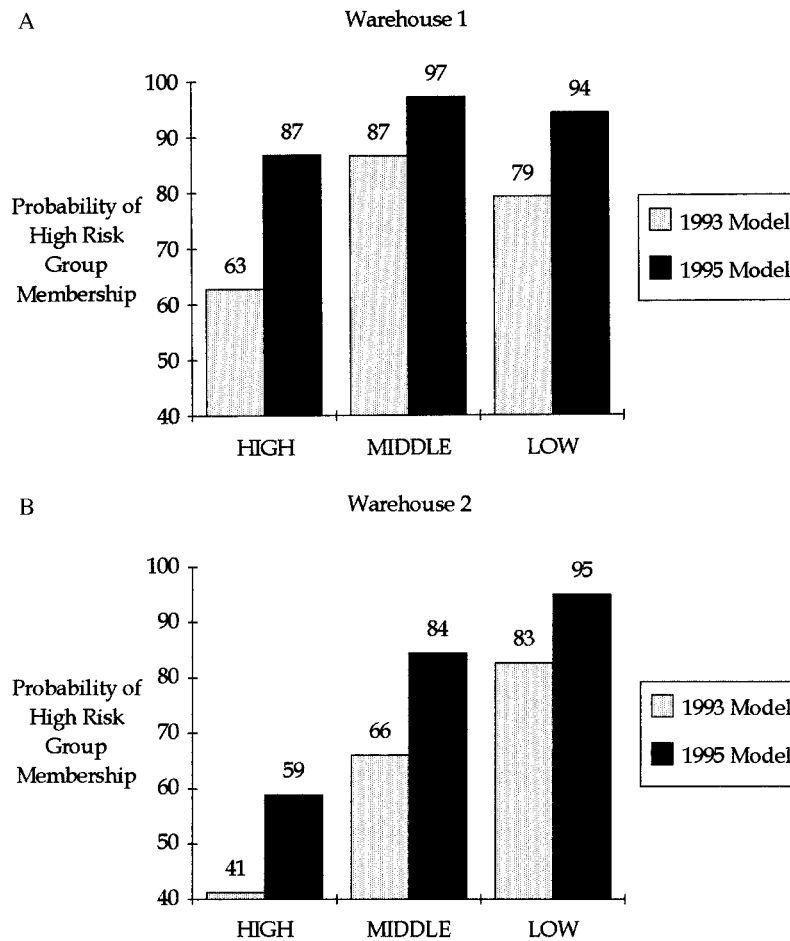


FIGURE 2. Summary of results using the 1993 and 1995 OSU models. A: Results of Warehouse 1; B: results of Warehouse 2.

work pulse, a term denoting the difference between the resting and working heart rates ($r^2=.61, p<0.1$). As shown in Table IV, there was a strong correlation between work pulse and working metabolic rate ($r^2=.80, p<0.02$), and between workload and working metabolic rate ($r^2=.77, p<0.05$).

EEPP

The mean predicted metabolic rate from the EEPP for the three participants in Study 1 was 6.2 kcal/min, and the mean working metabolic rate estimated from oxygen consumption was 6.4 kcal/

min. Although the data are limited, it appears that the EEPP provides a reasonably accurate estimate of energy expenditure (see Table IV).

SNOOK

The maximum-acceptable-weight-of-lift values shown in Table VI were derived from SNOOK⁽¹⁵⁾ by adjusting the values for extended reaches as suggested by the authors. Since most of the lifts performed by the grocery selectors required extended reaches and the boxes lacked handles, the maximum-acceptable-weight-of-lift

TABLE IV. Summary of Workload and Physiological Responses for Participants in Warehouses 1 and 2

Variable	Participant					
	1	2	3	4	5	6
Total cases/order	167	138	101	168	120	116
Total weight/order (lbs)	2198	4220	3862	4750	2522	1894
Allowed time/order (min)	34.9	36.7	25.8	51	38	43
Weight/min (lbs/min)	63	115	150	114	75	48
Performance index ^a (%)	116	116	143	122	113	106
Working metabolic rate (kcal/min)	5.5	5.8	7.3	6.3	4.0	2.6
Working heart rate (beats/min)	130	106	140	140	142	138
Predicted metabolic rate from EEPP (kcal/min)	6.0	5.0	7.6	—	—	—

^aPerformance index = (allowed time per order/actual time per order) × 100.

TABLE V. Results of Linear Estimation for Various Physiological Measures

Comparison Variables	m ^a	y ^b	r ²	F
Working heart rate vs working metabolic rate	-.02	7.8	.02	0.1
Work pulse ^c vs working metabolic rate	.24	-2.0	.80	15.6 ^d
Workload vs working heart rate	-.05	137.0	.02	0.1
Workload vs work pulse	.13	18.1	.61	6.3 ^d
Workload vs working metabolic rate	.04	1.6	.77	13.4 ^d

^am = slope

^by = y-intercept

^cWork pulse is defined as the difference between working pulse rate and resting pulse rate.

^dSignificant at $p < 0.05$

values in Table VI reflect a 57.5% reduction from those originally listed in the database. For comparison purposes, the values in Table VI correspond to a box width of 19.3 inches (49 cm) and a vertical displacement of 20.1 inches (51 cm). In most of the observed lifts, the vertical displacement exceeded 20.1 inches, which would result in even lower acceptable weight limits than shown in Table VI.

A comparison of a typical lift in Warehouse 2, as defined by the average weight of 29.2 lbs and the average frequency of 4.9 lifts/min for the 173 lifts analyzed, to the values in Table VI, reveals that the lifts are acceptable to less than 10% of the male industrial workforce. According to Snook et al.,⁽¹³⁾ lifting tasks should be designed so that at least 75% of the population find them acceptable. Therefore, when extrapolated from Table VI, the average weight lifted by grocery selectors for lifting tasks with a frequency of 4.9 lifts per minute should not exceed approximately 12.7 lbs for shoulder-to-reach lifts, 15.4 lbs for knuckle-to-shoulder lifts, and 13.6 lbs for floor-to-knuckle lifts.

Back Injuries and Back-Related Lost Workdays

A summary of total injuries, lost workdays due to injury, and back injury cases per 100 workers, and average number of lost workdays per back injury case, recorded on the OSHA 200 logs for grocery selectors at the two work sites are presented in Table VII. Due to differences in record keeping between the warehouses, data were not collected for both work sites for the entire period 1987 to 1992. In addition to the injury and lost workday data recorded on the OSHA 200 logs, 33% of all the workers in the two studies reported on a questionnaire that they had a back injury in the last 12 months, and 59% of all the workers indicated that they had back pain or discomfort that would be rated as "very or extremely uncomfortable."

TABLE VI. Psychophysical Weight Limits in Pounds for Males

Vertical Location	Lifts/Min ^a	Weight Acceptable to 75% of Males (lbs)	Weight Acceptable to 50% of Males (lbs)	Weight Acceptable to 10% of Males (lbs)
Floor to knuckle	6.7	12.1	15.8	23.3
	4.3	14.1	18.7	27.1
Knuckle to shoulder	6.7	14.1	17.8	24.4
	4.3	15.8	19.6	28.2
Shoulder to reach	6.7	11.2	16.9	20.7
	4.3	13.2	21.6	23.3

Source: Snook and Ciriello, 1991.

^aThe lift rates of 4.3 and 6.7 correspond to Snooks's rates of 1 lift every 14 and 9 seconds, respectively. These rates were used for comparison since the average lift rates observed in the warehouses fell between 4.3 and 6.7 lifts per minute. When interpolated for 4.9 lifts per minute, the acceptable weight for 75% of males is approximately 12.7 lbs for shoulder to reach lifts, 15.4 lbs for knuckle to shoulder lifts, and 13.6 lbs for floor to knuckle lifts.

DISCUSSION

These results provide a unique opportunity to qualitatively compare and contrast various aspects of the ergonomic assessment methods typically used to evaluate MMH tasks. This information should be particularly useful to job analysts who must make decisions regarding which assessment method to use for a particular MMH job.

Of the six methods used in this study, only the 3DSSPP, OSU, and NLE methods consider biomechanical criteria in assessing the physical demands of a manual lifting task. Because the three methods use different biomechanical criteria, and because the criteria are used in different ways, each method has advantages and disadvantages when compared with the others. For example, although limited to providing estimates of static loading, the 3DSSPP method provides information about muscle forces and torques for most articulation joints, including the spine and for joints other than those in the spine. This capability may be important to the user, who may be concerned about musculoskeletal problems in the shoulder or arms, rather than the low back. In comparison, the NLE equation does not provide biomechanical results directly, but instead provides a recommended weight limit that is based on a disc compression force limit of 3.4 kN. Researchers believe that high compression and shear forces in the spine are important in determining how much weight should be lifted to prevent injury to the spine.

It should be mentioned that freezing the posture to make measurements, as was done for the 3DSSPP method, could cause the worker to adopt an atypical posture that might result in an erroneous estimate of the biomechanical forces that would actually occur when the lift was performed at the normal speed. Since static biomechanical models assume zero acceleration, they do not require kinematic measurement and thus allow for the use of simple equations of static equilibrium. They are not capable, however, of predicting loads attributable to dynamic movements, in which the use of more complex equations of dynamic equilibrium are required.

Of the three methods that consider biomechanical loading, only the OSU model is capable of utilizing dynamic motion characteristics to assess physical stress. Therefore, the OSU model may be more appropriate for assessing tasks with significant dynamic movement that affect the spine.

Of the six assessment methods evaluated in this article, only the NLE, VO₂/HR measurement, and the EEP methods directly consider the physiological demands of the lifting activity. It has been hypothesized that the psychophysical approach provides weight limits that indirectly consider both the biomechanical and

TABLE VII. Injuries and Lost Workdays Recorded on the OSHA 200 Log

Year	Total Injuries per 100 Workers		Lost Workdays per 100 Workers		Back Injuries per 100 Workers		Lost Workdays per Back Injury (avg)	
	W1	W2	W1	W2	W1	W2	W1	W2
1987	79	—	557	—	28	—	15	—
1988	88	—	1452	—	31	—	34	—
1989	87	62	1157	90	39	21	18	4
1990	81	62	1775	160	31	31	44	14
1991	52	83	1191	174	28	29	34	7
1992	—	86	—	234	—	17	—	3

Note: W1 = Warehouse 1, W2 = Warehouse 2.

the physiological demands of the activity.⁽³¹⁾ The authors' findings indicated that there was poor correlation between working heart rate and workload. This is because working heart rate can be affected by a number of factors, including mental stress, digestion, work environment, and cardiovascular conditioning. For this reason, work pulse may provide a better measure of the effect of physical workload on the cardiovascular system. The authors were reassured, however, by finding a significant positive correlation between work pulse and workload and working metabolic rate.

The EEP procedure is limited when jobs with variable task characteristics are analyzed because (1) it is time consuming, sometimes requiring 1 hour or more of analysis time to analyze 5 minutes of work; (2) it requires a well-trained analyst; and (3) it requires development of a series of standardized decision criteria prior to the assessment. Benefits include a wide range of applicability and the ability to assess a job from a videotape recording. Also, estimates may be obtained for specific elements of the job, which can be used to determine the relative contribution of each activity to the total estimate of physiological demand. For example, individual estimates may be obtained for the lifting, pushing, pulling, carrying, standing, and walking components of a mixed-task job.

Care should be taken in assessing the physical demands of mixed-task jobs, however, because Straker et al.⁽³²⁾ has recently shown that acceptable weight limits are lower for combination tasks than for jobs consisting of one primary task type. This finding differs from previous assumptions that the level of risk associated with a mixed-task job is determined by the single most stressful activity performed by the worker.⁽³³⁾

Of the six methods evaluated in this study, only the NLE and the SNOOK methods consider the psychophysical data. According to the NLE the job of grocery selector will be unacceptable for nearly all healthy workers. According to the Snook and Ciriello data, less than 10% of the male population will find the job of order selector acceptable. Snook⁽¹³⁾ indicated that a worker was three times more susceptible to low back injury if performing a manual handling task acceptable to less than 75% of the working population.

Because more than one tool may apply to a particular job, other considerations such as estimates of ease of use, degree of training required, usefulness of results, cost of the equipment needed to obtain measurement data, labor requirements for collection and analysis of data, costs of work disruption, and the impact of the method on workers may be important determinants for selecting an assessment method. For example, a method may be scientifically valid for a particular job, but have little practical value because the results are not useful to the job designer. Also, the data collection equipment may be too costly for a small business. It is likely that these considerations may not be of equal importance to

an analyst, and that some form of weighting for individual criteria may be more appropriate.

In many cases an analyst wants to use the assessment results to determine the level of risk of musculoskeletal disorder associated with a particular job. In most cases it is not possible to determine a specific level of risk. It is more likely that the method will provide an accurate determination of the level of demand associated with a task. For example, the VO₂/EPP method does not provide information about the level of risk directly, but it does provide accurate data about the physiological demands of the activity. This may be very important in setting work limits, when high-frequency manual handling activities are required. In comparison, the LMM/OSU method shown in Figures 1 and 2 is designed to provide an estimate of the probability that a job would be a member of a high-risk group. The range of probability found in this study (41 to 95%), however, makes it difficult to interpret what the overall risk of LBD is for a typical worker. It should be noted that these were highly demanding jobs and that different results might have been obtained had the job been less physically demanding.

The variability in task characteristics associated with the grocery selector job presents a problem for nearly all of the assessment methods. When the conditions vary significantly between exertions, it is difficult to evaluate the physical demands accurately. The physiological approach may be best suited for variable work environments because it is possible to average the loading across a number of exertions. This is more difficult for biomechanically or psychophysically based methods. More research is needed to develop sampling methods that allow integration of these loads across the shift.

Finally, it should be noted that most of the methods are sensitive to the assumptions about their use. For example, the SNOOK method is sensitive to assumptions about the location of the load during the lift. In the analysis of the lifting tasks performed by the grocery selectors, it was observed that the job of grocery selector typically requires extended reaches. Therefore, the psychophysical data as suggested by the developer was adjusted. If it had not been assumed that extended horizontal reaches were used, then the Snook data would indicate that the grocery selector task was acceptable to more than 50% of male workers, and would not represent as significant a risk of low back pain as before.

Based on knowledge of the underlying criteria used to develop each of the assessment methods, the authors developed the chart shown in Table VIII. The chart graphically illustrates where the authors believe each of the assessment tools would be applied most appropriately. For a moderate frequency lifting task, for example, the chart suggests that either the NLE, OSU, or SNOOK methods should be used. For a mixed task with frequent repetitions, however, a physiological method would probably be more

TABLE VIII. Assessment Tool Selection Chart

Task Activity	Tool				
	3DSSPP	LMM/OSU	VO2/EEPP	SNOOK	NLE
Lift/lower					
Frequent		■	■		■
Moderate		■		■	■
Infrequent	■				■
Push/pull					
Frequent			■		
Moderate				■	
Infrequent	■				
Carrying					
Frequent			■		
Moderate				■	
Infrequent	■				
Mixed					
Frequent			■		
Moderate				■	
Infrequent	■				

appropriate. Some methods are frequency dependent, such as the 3DSSPP method, which applies to nearly any type of infrequent task, or the SNOOK method, which is more reasonable for tasks performed at intermediate frequencies.

Further analysis of Table VIII indicates that there are differences between the methods regarding what type of job and what task frequencies are appropriate. For example, the NLE and OSU methods apply only to lifting, while the 3DSSPP, VO2/EEPP, and SNOOK methods apply equally well to lifting, pushing, and pulling tasks. However, the OSU and NLE methods are appropriate for a wider range of task frequencies than the 3DSSPP, VO2/EEPP, or the SNOOK method. This suggests that there may be a tradeoff between the range of appropriate job types and task frequencies.

From the experience of analyzing the grocery selector job with the assessment methods presented in this article, Table IX was developed to assist in understanding the differences between the assessment tools. Table IX contains a partial list of the strengths

and weaknesses of the various assessment methods used in this study.

CONCLUSIONS

Based on the results obtained from the two grocery warehouses, it is apparent that all six of the ergonomic methods used in this study indicate that the job of grocery selector has a high level of risk for low back pain. This conclusion is in agreement with the injury data obtained from the OSHA 200 logs and from the responses of the workers themselves.

Nevertheless, analysis of the results suggests that there are significant differences among the various methods, and that these differences may be important when deciding which assessment method to use when evaluating a specific manual handling job. Since each method has limitations that determine when and how the method should be used, no single method will be sufficient to assess every manual handling task. Moreover, previous research has shown that a complete evaluation of a task should incorporate more than one method.^(16,34) It is important to decide what criteria are important before choosing an assessment method. For example, a user with little or no training or experience in job analysis might prefer the Snook or NLE for a manual lifting job. If it is impractical to use these methods because the information they provided does not adequately address the concerns of the user, or the method does not apply to the job to be evaluated, then the user may need to acquire additional training or seek assistance from a person with broader experience. Proper selection of assessment methods requires that the analyst have a thorough understanding of the various weighting factors, as well as the limitations of the methods. Other assessment methods that were not evaluated could easily be evaluated according to the criteria presented previously.

ACKNOWLEDGMENTS

The authors would like to acknowledge the contributions of Mr. Glenn Doyle and Mr. Pete Fatone for their valuable assistance in collecting and analyzing the data.

TABLE IX. Strengths and Weaknesses of Ergonomic Assessment Tools

Assessment Method	Strengths	Weaknesses
NLE	Easy to use Economical Wide range of criteria	Applies only to lifting Requires many assumptions
3DSSPP	Provides detailed estimates of mechanical forces on the body Can identify specific body structures exposed to high risk	Not applicable to repetitive activities Does not apply to highly dynamic activities Difficult to obtain input data
LMM/OSU	Provides direct measures of postural kinematics Able to consider dynamic loading factors	Worker must wear the device during the work activity Applies only to lifting tasks
VO2/EEPP	Provides detailed estimates of physiological demands for repetitive work Applicable to a wide range of MMH activities	Not applicable to infrequent activities
SNOOK	Easy to use Provide population estimates of worker capacities Applicable to a wide range of MMH activities	Significant effort required to obtain accurate data May over- or underestimate demands for infrequent or highly repetitive activities Based on what worker will accept, not what is safe

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