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Developing Physical Exposure-Based Back Injury Risk Models Applicable to Manual Handling Jobs in Distribution Centers

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Using our ultrasound-based "Moment Monitor," exposures to biomechanical low back disorder risk factors were quantified in 195 volunteers who worked in 50 different distribution center jobs. Low back injury rates, determined from a retrospective examination of each company's Occupational Safety and Health Administration (OSHA) 300 records over the 3-year period immediately prior to data collection, were used to classify each job's back injury risk level. The analyses focused on the factors differentiating the high-risk jobs (those having had 12 or more back injuries/200,000 hr of exposure) from the low-risk jobs (those defined as having no back injuries in the preceding 3 years). Univariate analyses indicated that measures of load moment exposure and force application could distinguish between high (n = 15) and low (n = 15) back injury risk distribution center jobs. A three-factor multiple logistic regression model capable of predicting high-risk jobs with very good sensitivity (87%) and specificity (73%) indicated that risk could be assessed using the mean across the sampled lifts of the peak forward and or lateral bending dynamic load moments that occurred during each lift, the mean of the peak push/pull forces across the sampled lifts, and the mean duration of the non-load exposure periods. A surrogate model, one that does not require the Moment Monitor equipment to assess a job's back injury risk, was identified although with some compromise in model sensitivity relative to the original model.

Keywords back injury, low back pain, musculoskeletal disorders, MSD, distribution center, load moment

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INTRODUCTION

Low back disorders have been associated with occupational manual lifting tasks. In fact, retrospective studies[(1,2)] of industrial injuries have identified manual material handling (MMH) as the most common cause of back injuries. It is estimated that lifting and MMH account for 50% to 75% of all back injuries.[(1–3)]

One of the industries with a considerable amount of manual material handling is transportation and warehousing. In the United States in 2009, the transportation and warehousing sector had the highest incidence rate for back pain (15.9 cases per 10,000 full-time workers). In the 1980s and1990s, National Institute for Occupational Safety and Health (NIOSH) investigations documented the prevalence and incidence of low back pain in grocery distribution centers, as well as biomechanical and ergonomic stresses.[(4–6)] These investigations concluded that grocery order pickers are at risk for back injury due to the combination of working postures, biomechanical factors, and metabolic demands, which could lead to fatigue.

One of the challenges facing ergonomists and researchers trying to evaluate risk in distribution center jobs is how to characterize risk factor exposures. Unlike manufacturing jobs where a limited number of items may be handled, distribution center (DC) workers are exposed to constantly changing lifting conditions that often include handling many different objects of different weights. For example, Lavender et al.[(7)] in an ergonomic evaluation of 53 automotive parts distribution centers jobs noted considerable variability in the weight of the parts handled. Characterizing the variability in biomechanical risk factor exposures across the large number of lifts performed has been problematic for many of the quantitative back injury risk assessment methods.

The objective of this work was to develop a methodology to assess back injury risk in distribution center jobs that could accommodate the within-job variability in risk factor exposures found in this type of work. Given that the onset of back pain is believed to have a mechanical origin,[(8,9)] in part due to its long-standing association with heavy work,[(10)] one of the primary research questions was how to best quantify the highly variable biomechanical loading exposures experienced in DC operations.

A number of parameters could be used to characterize the biomechanical exposure in DC MMH tasks. For example, individual lifts could be characterized by the weight of the object lifted, the maximum reach distance, the peak in the load moment over time (weight lifted multiplied by the maximum reach distance), the dynamic load moment, the heights at the beginning and end of the lift, the asymmetry relative to the mid-sagittal plane, plus many more. In prior studies evaluating manufacturing jobs, Marras et al.(11) reported that the load moment by itself was a stronger predictor of back injury risk than either version of the NIOSH lifting equation. This finding led us to hypothesize that parameters based on the load moment would be effective exposure metrics capable of predicting back injury risk in distribution center jobs.

Moreover, given the cumulative trauma nature of occupationally related back injury(12–14) that temporal indicators of exposure to physical loading should also contribute toward the prediction of back injury risk. Once these types of measures—which describe the exposures associated with each individual lift or exertion— are obtained, the total job exposure still needs to be characterized, perhaps as the mean value across the sampled lifts or perhaps some other percentile value that better differentiates exposures across risk groups.

METHODS

Approach

This study was part of a larger prospective study that involved 888 MMH workers from 21 distribution centers. This study used the job as the unit of analysis. For each of the jobs sampled, physical exposure and health effects were assessed. Physical exposures were monitored using new instrumentation, the Moment Monitor, for up to 4 hr in three to seven individuals performing each job. These physical exposure measurements were obtained from 195 distribution center workers. Historical injury rates in each of the sampled jobs were obtained by reviewing OSHA 300 data for the 3 previous years. Discussions with representatives from the participating organizations suggested that, biomechanically, the work methods in our sampled jobs had not changed during this 3-year period. Thus, the retrospective injury data should be representative of current work exposures.

Sample

Fifty jobs were identified in the 21 distribution centers in which employees perform repetitive material handling tasks throughout the day. Across these jobs, a variety of products were handled. Eleven jobs handled groceries, 5 jobs handled other food products, 13 jobs handled general merchandise, 7 jobs handled automotive parts, 10 jobs handled apparel, and 4 jobs handled a variety of other products (hair care, paper, hardware, furniture). Sites were selected based on location, quality of injury reports, and willingness on the part of management to work with the investigators.

Given the similarity of jobs within distribution centers, jobs were differentiated based on the department (or section) if workers did not float from one department to another. For example, a grocery distribution operation may have had three to four jobs, depending on how orders are distributed. Usually employees "picked" in dry groceries, produce, frozen foods, or boxed meats. Therefore, a grocery facility with these four areas would have contributed four jobs to the sample. In general merchandise distribution centers, where employees essentially handled any item in the warehouse, there may be only one "picking" or "selecting" job defined for the facility. However, often these facilities had people manually loading and/or unloading trucks on the shipping or receiving docks, thereby contributing additional jobs to the sample. Jobs were included in the sample if: (1) there were three or more workers, (2) there was a discrete job title for injury reporting purposes, (3) the majority (e.g., >80%) of handled items (boxes) could be lifted using instrumented handles, (4) the workers did not drive equipment in a seated posture, and (5) the ambient temperature in the environment was greater than 0° Celsius.

The 50 jobs in the sample included a population of 888 workers. From this population, we recruited up to five volunteers from each job for the load moment exposure measurements (this number may be less if only a small number of employees performed the job or if the volunteer rate was low). From the 50 different warehouse jobs, 195 volunteers participated in the biomechanical exposure data collection. Table I describes the anthropometry and the experience level of the workers sampled in the low- and high-risk jobs (discussed below). Participants signed an informed consent document and were compensated for their participation with gift cards from area merchants. Each employee was monitored for up to 4 hr that, given normal productivity requirements, could have included several hundred lifts. In some cases, shorter sampling periods were used if the full range of exposure data that were representative of the job could be obtained with shorter sampling periods. Facility management helped

TABLE I. Demographics of Sampled Individuals from the Low and High-Low Back Injury Risk Groups Who Wore the Backpack

	Low Risk (n = 56)		High Risk (n = 59)	
Measure	Mean	SD	Mean	SD
Age (yrs)	38	10	35	12
Percentage of males	70	46	83	38
Weight (kg)	78	16	85	17
Stature (cm)	173	10	176	8
Arm length (cm)	73	5	73	5
Job experience (months)	46	46	53	48
Percentage with prior LBP	43	50	36	48

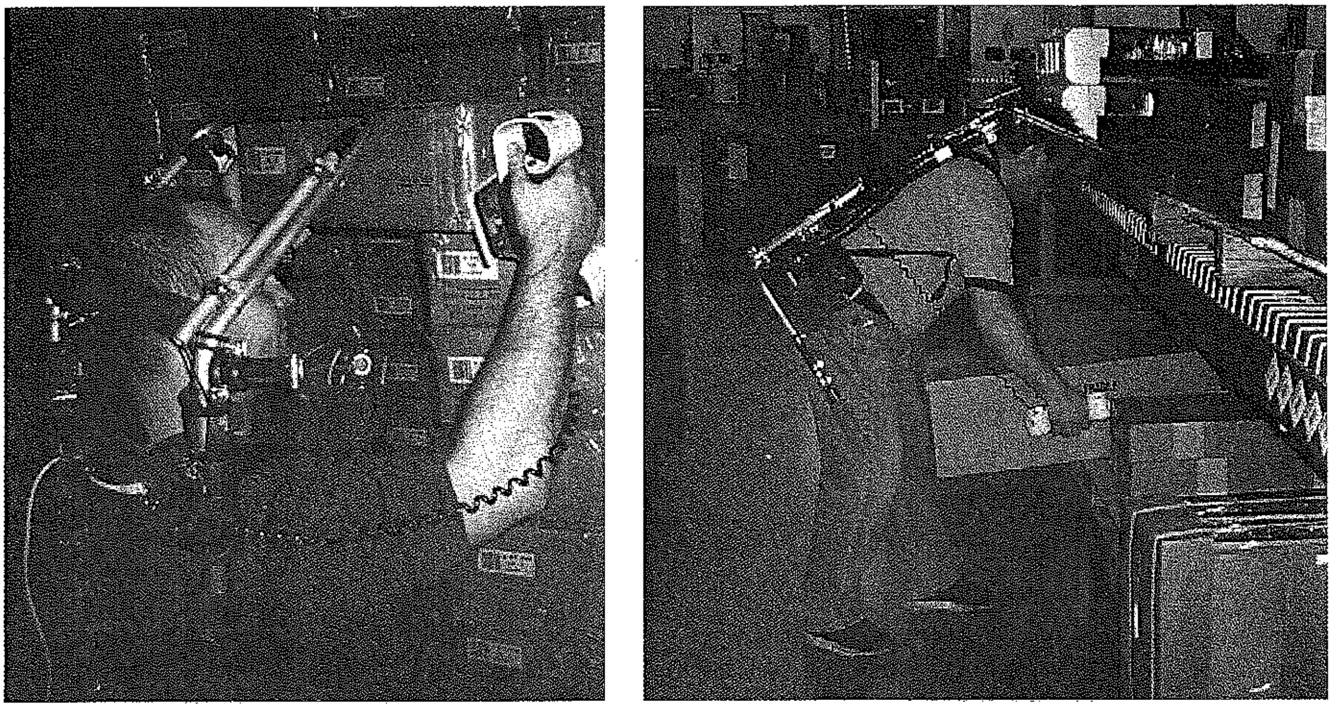

FIGURE 1. Participants wearing the Moment Monitor backpack while performing material handling tasks in distribution centers. The instrumented handles provided force information and emitted the ultrasonic signals picked up by the receivers on the backpack frame.

us identify "typical" workloads for each job, which aided in developing our sampling strategy at each site.

Apparatus

Load moment exposure data were obtained using the Moment Monitor instrumentation. A full description of this instrumentation, its development, and its evaluation with regard to accuracy has been published elsewhere.(15) The instrumentation (Figure 1), built onto a backpack frame, was capable of monitoring the static and dynamic load moments from each exertion (lift, lower, push or pull) a participant made during the observation period. Instrumented handgrips measured the items' weights and accelerations and provided ultrasound emissions that were received by sensors on the backpack frame. The ultrasound signals, sampled at 12.5 Hz, were triangulated to determine hand location relative to L5/S1. The instrumentation functioned as an automated data collection system that continuously monitored 3D hand locations, the instantaneous load, the global orientation of the torso, and the timing of lifting events. The accuracy of the system during dynamic tracking had average absolute error of 3.8 cm relative to a magnetic tracking system, which compares favorably with the 10.9 cm error obtained during manual measurements.(15) The force measuring handles had a very linear relationship with the true load ($r^2 = .99$).(15) The handgrips could be holstered when not in use, for example, when driving stand-up material handling equipment. Five backpacks were available, which allowed for five employees to be sampled at the same time. Each backpack data collection system weighed 5 kg.

Procedure

Each volunteer reviewed and signed informed consent documents approved by the university's institutional review board. Participants were instrumented with the backpack and given an opportunity to practice with the handgrips used when handling boxes before initiating their work.

Participants were instructed to work as close to their normal pace as possible even though productivity standards were typically relaxed for the participants. This was necessary to obtain accurate temporal data regarding the periods of time between biomechanical exposures and accurate cumulative exposure data.

Each participant was followed by a member of the research team who would primarily be observing unit integrity, and keeping track of the type of work performed and, whether there were any situations that would introduce irregularities into the data stream being recorded on the unit's flash memory card. The backpacks were removed during scheduled break periods.

Data Analysis

While 50 jobs were sampled, 3 were removed from the analysis due to equipment malfunction, leading to insufficient data. The final sample of 47 jobs netted a database containing a total of 58,796 exertions. Custom software was developed to analyze each of the exertions. Included in the load

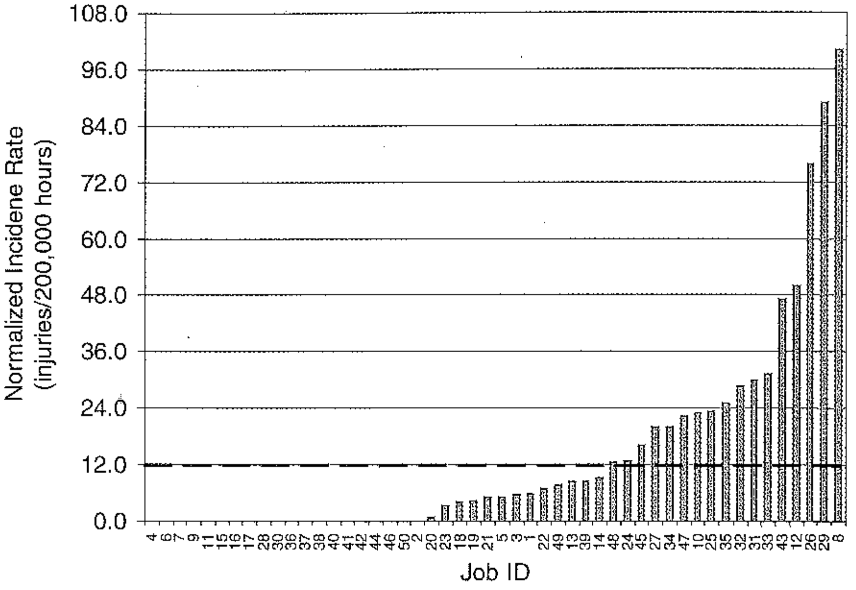

FIGURE 2. The distribution of normalized injury rates from the sampled jobs. The dashed line at 12 injuries per 200,000 hours represents the high-risk threshold used in the analyses.

moment exposure database were 227 parameters characterizing each lift. In general, these exposures variables can be categorized as: (1) load magnitude-related variables including box weights, static and dynamic three-dimensional moments and their directional components, forward and lateral push and pull forces; (2) load position-related variables including load origins and destinations heights and reach distances, as well as load velocity and acceleration; (3) trunk kinematic variables characterizing spine positions, velocities, and accelerations; and (4) timing-related variables (lift durations, time of peak loadings, lifting frequencies, time between lifts, and so on). For the load magnitude, load position, and trunk kinematic variables, parameters from each lift included minimum, mean, and maximum values where it made sense to evaluate such parameters. In addition, for some variables, the data were rectified so that mean and peak magnitudes that were independent of the direction components could be obtained.

Injury data were normalized to an exposure period of 200,000 hr, thereby converting the incidence data into an injury rate for each sampled job. The distribution of injury rates for the sampled jobs is shown in Figure 2. For modeling purposes, the 15 jobs with no recorded injuries over the prior 3 years were categorized as "low-risk" jobs. The 15 jobs with injury rates in excess of 12 injuries/200,000 person-hours, a rate used to dichotomize the sample in the lumbar motion monitor study,(12) were classified as high-risk jobs. When computing the descriptive statistics and formulating the risk models, the 17 jobs in between these cut points were removed from the analysis. For each job, descriptive statistics were computed for all variables, and distribution plots were generated for the load moment exposure variables. Univariate logistic regression models were developed for variables using the normalized incident rate data as the outcome variable. Significant variables were identified through the univariate analysis to screen variables for further inclusion in multivariate models. Odds ratios (OR) and correlation coefficients were calculated for each predictor individually. The goal was to find the best set of load moment and duty cycle variables that could predict incident rate classifications. To avoid overspecified models, no more than three predictors were allowed in a model, following the rule that the number of predictors should be no more than 10% of the number of observations. Classification and regression tree software (Version 6.0, CART, Salford Systems, San Diego, Calif.) was used as a variable selection tool for building the final statistical models.(16,17)

RESULTS

Univariate Results

Tables II and III show the means (and standard deviations) for the low and high back injury risk groups, as well as the univariate odds ratios for the load variables, the work kinematic variables, and the temporal variables. On average the loads handled by those in the high-risk groups were heavier, resulted in larger static and dynamic moments about L5/S1, and were associated with larger sliding forces (Table II). The highest univariate odds ratios were dynamic twisting slide moment (OR = 2.39), the static side-bend load moment (OR = 1.42), and the dynamic side-bend load moment (OR = 1.41).

Relative to the back injury risk group, the maximum forward moment arm (applied for sliding forces) and the peak box vertical deceleration were significantly larger in the high back injury risk group (Table III). It is notable that there was little difference in the spine kinematics across these DC workers

TABLE II. Mean and Univariate OR for Load Variables

Variable (Units)	Mean (SD) Low-Risk	Mean (SD) High-Risk	Beta	Std. Error	OR	95% CI	
Abs. max dynamic twisting slide moment (nm)	4.04 (1.25)	6.08 (2.52)	0.870	0.173	2.39	1.70	3.35
Abs. max static side-bend load moment (nm)	9.35 (2.24)	12.31 (2.90)	0.351	0.068	1.42	1.24	1.62
Abs. max dynamic side-bend load moment (nm)	10.00 (2.64)	13.42 (3.40)	0.343	0.064	1.41	1.24	1.60
Abs. max dynamic forward-bend slide moment (nm)	8.88 (2.55)	12.58 (4.59)	0.329	0.065	1.39	1.22	1.58
Abs. max dynamic lateral plane slide moment (nm)	9.58 (2.73)	13.63 (4.98)	0.324	0.063	1.38	1.22	1.56
Abs. average dynamic transverse plane load moment (nm)	18.70 (5.00)	23.60 (3.98)	0.232	0.044	1.26	1.16	1.37
Abs. average dynamic resultant moment (nm)	19.90 (5.13)	25.58 (4.17)	0.215	0.041	1.24	1.15	1.34
Abs. average static transverse plane load moment (nm)	20.15 (5.22)	25.84 (5.28)	0.184	0.038	1.20	1.12	1.29
Abs. max static transverse plane load moment (nm)	29.07 (6.90)	37.75 (7.55)	0.128	0.026	1.14	1.08	1.20
Abs. max static forward-bend load moment (nm)	28.40 (6.80)	36.91 (7.39)	0.130	0.026	1.14	1.08	1.20
Abs. max dynamic slide force (n)	35.67 (11.66)	49.43 (17.59)	0.118	0.023	1.13	1.08	1.18
Abs. max dynamic forward-bend load moment (nm)	35.20 (10.68)	46.81 (10.86)	0.087	0.018	1.09	1.05	1.13
Abs. max dynamic transverse plane load moment (nm)	36.16 (10.91)	48.07 (11.16)	0.086	0.017	1.09	1.05	1.13
Abs. max dynamic forward-bending resultant (sagittal) moment (nm)	35.49 (10.60)	47.71 (11.19)	0.084	0.017	1.09	1.05	1.13
Abs. max dynamic resultant moment (nm)	36.56 (10.84)	49.17 (11.60)	0.083	0.017	1.09	1.05	1.12
Load weight (n)	57.17 (11.01)	71.82 (13.65)	0.078	0.016	1.08	1.08	1.12
Max dynamic lift force (n)	85.18 (20.89)	110.56 (26.17)	0.045	0.009	1.05	1.03	1.06
Abs. max dynamic lift/slide force (n)	91.22 (22.71)	120.58 (29.29)	0.046	0.009	1.05	1.03	1.07
Max dynamic left side-bend load moment (nm)	–6.55 (1.73)	–9.53 (2.88)	–0.474	0.088	0.62	0.52	0.74
Max static left side-bend load moment (nm)	–6.54 (1.61)	–9.34 (2.51)	–0.521	0.092	0.59	0.50	0.71

Notes: Table is sorted by magnitude of the OR. All variables were significant, as their confidence intervals did not include 1.0.
Max is the maximum value of the quantity being measured during each sampled exertion.
Abs refers to the absolute value of a quantity, thereby negating directional effects.
Static indicates the absence of dynamic contributions in the measured quantity.
Dynamic indicates the dynamic component of the load were included when obtaining the parameter.
Abs. average is the average of the absolute value of the time varying quantity across the exertion period.
Load moment is based on the vertical applied force.
Slide moment is based on the horizontal component of the applied force.
Resultant moment is based on the vector sum of the horizontal and vertical components of the applied force.

based on the low- and high-risk back injury rate classification. The means indicate that both high- and low-risk jobs required substantial forward and lateral bending. Likewise, workers in both high- and low-risk distribution center jobs were lifting frequently, i.e., in excess of 150 times per hour.

Multivariate Model for Predicting Back Injury Risk Group Membership

Multivariate models were constructed by selecting the biomechanical variables that had strong univariate results and combining these with variables representing the temporal loading exposures. Each candidate variable was converted to a dichotomized variable using the cut points identified with the CART software. Models were evaluated based on their sensitivity and specificity, as well as their explanatory power. This process resulted in the three-variable model shown in Table IV that included the mean of the job's peak transverse plane dynamic load moments, the mean of the job's non-load exposure intervals, and the mean of the job's peak horizontal forces. The mean of the peak transverse plane dynamic load moments was calculated by determining the load's maximum bending moment on the spine that occurred during each lift, irrespective of whether it was a forward bending or lateral bending moment. These maximum load moments were then averaged across all the lifts performed by all participants sampled in the job. Likewise, the mean of the job's peak horizontal forces were obtained by extracting the peak horizontal force during each lift, which was usually a pull force but could have also been a push force, and averaging these peak values across all lifts performed by all the participants sampled in the job. The mean non-load exposure period was obtained by calculating the mean duration of the periods between lifts across all participants sampled in the job.

The probability that a job would have more than 12 incidents per 200,000 hours of exposure if one or more of the variables in the model exceed threshold values is given by the following

TABLE III. Means and Univariate OR for Variable Groups

Variable Group	Variable (Units)	Low-Risk Mean (SD)	High-Risk Mean (SD)	Beta	Std. Error	OR	95% CI	
Moment Arm	Abs. Max Sagittal Plane Moment Arm (cm)	57.67 (6.53)	59.13 (3.60)	0.042	0.036	1.04	0.97	1.12
	Abs. Max Forward Moment Arm (cm)	**16.16 (1.63)**	**17.06 (2.06)**	**0.327**	**0.096**	**1.39**	**1.15**	**1.67**
	Start Transverse Plane Moment Arm (cm)	42.95 (5.04)	44.76 (3.13)	0.101	0.05	1.11	1.00	1.22
	Max Transverse Plane Moment Arm (cm)	50.06 (5.36)	51.81 (3.36)	0.081	0.044	1.08	1.00	1.18
	Abs. Max Lateral Plane Moment Arm (cm)	50.06 (5.36)	51.81 (3.36)	0.081	0.044	1.08	1.00	1.18
	Max Resultant Moment Arm (cm)	58.68 (6.52)	60.15 (3.71)	0.045	0.035	1.05	0.98	1.12
Temporal Variables	Duration (sec.)	2.34 (0.69)	2.55 (0.91)	0.182	0.198	1.2	0.81	1.77
	Duration of non-load exposure (sec.)	19.02 (11.32)	21.32 (11.99)	–0.018	0.017	0.98	0.95	1.01
	Frequency (lifts/min)	2.69 (1.32)	2.54 (1.58)	0.134	0.132	1.14	0.88	1.48
Box Acceleration	Max Box Up Acceleration (m/sec^2)	9.73 (4.40)	12.09 (5.68)	0.059	0.033	1.06	0.99	1.13
	Max Box Up Deceleration (m/sec^2)	**–5.07 (1.88)**	**–6.04 (2.14)**	**–0.185**	**0.086**	**0.83**	**0.70**	**0.98**
Lifting Height	Start Height (cm)	89 (1.1)	91 (0.9)	–0.019	0.017	0.98	0.95	1.01
	End Height (cm)	103 (1.7)	107 (0.9)	.0.031	0.014	1.03	1.00	1.06
Spine Kinematics	Abs. Max Sagittal Trunk Angle (degrees)	52.31 (13.72)	50.45 (8.90)	0	0.016	1.00	0.97	1.03
	Abs. Max Lateral Trunk Angle (degrees)	17.12 (1.94)	17.01 (2.18)	0.018	0.083	1.02	0.87	1.20
	Max Sagittal Trunk Flexion Velocity (deg/sec)	69.12 (17.75)	68.96 (18.77)	–0.014	0.01	0.99	0.97	1.01
	Max Sagittal Trunk Extension Velocity (deg/sec)	–85.49 (15.17)	–83.61 (16.28)	–0.007	0.012	0.99	0.97	1.02
	Abs. Max Lateral Trunk Velocity (deg/sec)	103.51 (13.20)	101.82 (19.37)	–0.012	0.01	0.99	0.97	1.01
	Max Sagittal Trunk Acceleration (deg/sec^2)	676.78 (102.83)	678.25 (159.13)	0	0.001	1.00	1.00	1.00
	Max Lateral Trunk Acceleration (deg/sec^2)	842.52 (117.93)	824.35 (169.23)	–0.001	0.001	1.00	1.00	1.00

Notes: Table has been sorted by the magnitude of the odds ratio. Significant odds ratios (those with confidence limits that do not include 1.0) are shown in **bold**.

equation:

$$\Pr(\text{High Risk}) = 1/(1 + 1/e(-2.938 + X_1 * 1.739 + X_2 * 2.488 + X_3 * 2.402)) \qquad (1)$$

where

$X_1 = 1$ if the mean duration of non-load exposure periods < 24.2 sec; else $= 0$

$X_2 = 1$ if the mean of the peak dynamic transverse plane load moments > 45.0 Nm else $= 0$

$X_3 = 1$ if the mean of the peak horizontal forces > 38.9 N else $= 0$

With dichotomized variables, the probability of a job being high risk can be calculated for the eight possible outcomes with respect to the 0 or 1 state of the variables in the model. These probabilities are shown in Table V.

Model Evaluation

Figure 3 shows a cross plot of the risk level predicted by the model as a function of historical injury rates. The figure shows that 13 out of 15 jobs with back injury rates exceeding 12 injuries/200,000 hours of exposure had predicted probabilities of being classified high-risk jobs that were greater than 70%. Three of the jobs considered low risk based upon the actual injury data were misclassified as high risk (for example,

TABLE IV. Multivariate Models Predictive of Low Back Disorder Risk

Model Performance	Variable	Cut Point	Estimate	Std. Error	Wald Score	p-value	Odds Ratio	Confidence Interval
	Intercept		–2.938					
Instrumentation-Based Model	Mean duration of non-load exposure period	High Risk <24.2 seconds	1.739	.580	8.98	.0027	5.69	1.83–17.74
Sensitivity = 87%	Mean of the peak dynamic transverse plane load moments	High Risk >45.0 Nm	2.488	.525	22.49	.0001	12.04	4.31–33.66
Specificity = 73%	Mean of the horizontal force peaks	High Risk >38.9 N	2.402	.507	22.42	.0001	11.04	4.09–29.85
Non-Instrumented Model	Intercept		–3.274					
Sensitivity = 93.0	Mean duration of non-load exposure period	High Risk <24.2 seconds	2.711	.525	26.65	.0001	15.04	5.37–42.10
Specificity = 60.0	Mean of the peak static transverse plane load moments	High Risk > 35.0 Nm	3.006	.516	34.00	.0001	20.20	7.36–55.49

Pr(high risk) > .70) by the model. The remainder of zero injury rate jobs had model generated probabilities of being high-risk values that were less than 40%.

Surrogate Model

While the model above comprises variables that collectively did well at differentiating the risk groups, two of the identified variables require the moment monitor instrumentation. We performed a second multivariate analysis using variables that could be assessed without the instrumentation to develop what we termed a "surrogate model." In this process we identified variables that could be measured using common instrumentation (for example, a scale and a tape measure) but correlated well with the variables in the original model. This analysis found that the mean of the job's peak static transverse plane load moment could be used along with the mean duration of the non-load exposure period. The mean peak static transverse plane load moment was the average of most extreme static load moment values that occurred during each sampled lift across all lifts performed by participants sampled in the job. These would typically occur at the beginning or end of a lift, where the moment arms were longest. This two-variable model had a sensitivity of 60% and a specificity of 93%. When using this model, the probability that a job would have more than 12 incidents per 200,000 hours of exposure if one or both variables exceed threshold values is given by the following equation:

$$\text{Pr(High Risk)} = 1/(1+1/e(-3.278+X_1*2.711+X_2*3.006)) \quad \textbf{(2)}$$

where

$X_1 = 1$ if the mean duration of non-load exposure periods < 24.2 seconds; else = 0
$X_2 = 1$ if the mean of the peak static transverse plane load moments > 35 Nm else = 0

DISCUSSION

This study used new instrumentation to characterize exposures to biomechanical risk factors predictive of back injury as determined via OSHA log data in distribution center jobs requiring manual lifting. Univariate analyses indicated

TABLE V. Pr(High-Risk) as a Function of the State of the Dichotomous Variables in the Model

Variables in the Model	Coefficient	Threshold Exceeded (Y or N)							
Mean duration of non-load Exposure period (sec)	1.74	N	Y	N	N	Y	Y	N	Y
Mean of horizontal force peaks (N)	2.40	N	N	Y	N	Y	N	Y	Y
Mean of peak dynamic transverse Plane load moment (Nm)	2.49	N	N	N	Y	N	Y	Y	Y
Pr(>12 incidents/200,000 hours)		0.05	0.23	0.37	0.39	0.77	0.78	0.88	0.98

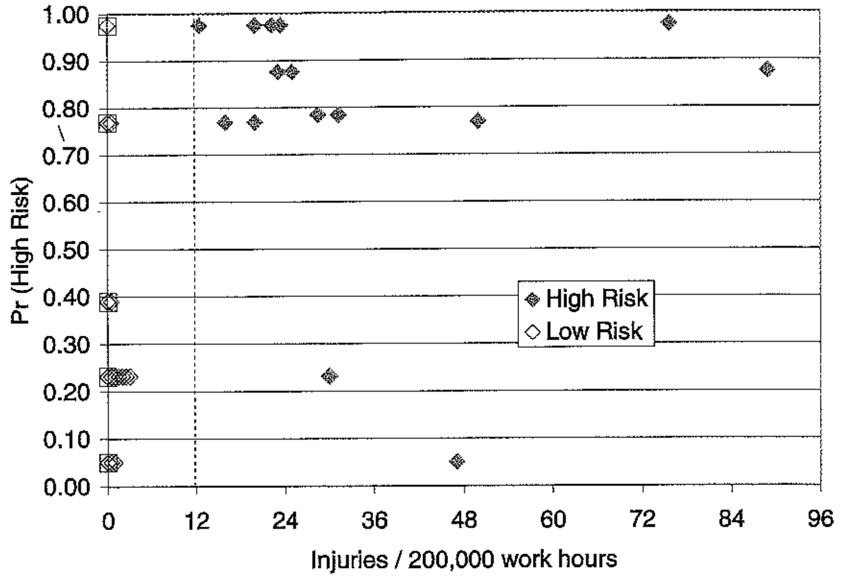

FIGURE 3. A plot of the historical injury rates vs. the predicted back injury risk obtained using the three-variable model for the 15 high-risk and 15 low-risk jobs used to create the model. Note that the historical injury rates in the low-risk jobs are all zero. The points in the graph have been offset so they are not covering one another.

that many of the biomechanical variables could be used to predict back injury risk; however, only selected kinematic and timing variables were predictive of back injury risk in these univariate analyses.

Even though there were few statistically significant differences in torso kinematics across the risk groups, the kinematic data indicated there was substantial trunk movement in nearly all the distribution center jobs sampled. Average maximum sagittal trunk angle observed in the current study was 50.3°. The maximum sagittal and lateral trunk velocities were about 70–80°/sec. Likewise, the maximum sagittal and lateral accelerations were also very high. These findings suggest that most MMH jobs in distribution centers involve considerable forward bending and quick motions.(18)

Since there were many significant variables in the univariate analysis, and given that the final model should not be overspecified, it was not possible to include and evaluate all combinations of the significant variables in the multiple logistic regression models. Therefore, a categorization method was used to facilitate variable selection in a way that provides the models with biological plausibility. The logic behind this method is that back injuries are a multifactorial disorder whereby biomechanical, psychosocial, and individual factors all potentially contribute to their development. In the National Research Council review of work-related musculoskeletal disorders,(19) lifting and carrying loads, frequent bending and twisting, and heavy physical work were all associated with increased risk of back injury. The categories (load moment, position/kinematics, temporal variables) used in the current study best represent the force, posture, and frequency characteristics of the risk factors. Therefore, the three-variable multivariate models included variables from these categories. This approach led to the development of sensitive and specific models that contained two biomechanical exposure variables and a variable describing the duty cycle (non-load exposure period).

The three variables selected in the multivariate model have strong biomechanical implications. Validated three-dimensional models of spine loading have demonstrated how increases in load moment increase the compression, shear, and torsion forces on the spine.(20–30) Spine loading in excess of the 3400 N tolerance limit may cause endplate damage, malnutrition of the disc, and eventually disc degeneration or herniation.(31) Task asymmetry increases the lateral component of the load moment that, in turn, impacts the lateral bending and torsional moments acting on the spine, as well as the spine compression and shear forces.(26,32) Task asymmetry often leads to lateral bending and or twisting motions. Previous studies have shown more complex muscular co-contraction patterns, especially when lateral bending or twisting was involved.(33–35) Marras and Granata(28) showed that including muscle coactivity in their model of lateral bending exertions increased their estimates of spine compression, AP shear, and lateral shear. Given that spine tolerance to shear forces is much lower than to compression,(36) lateral trunk load moments would likely impose significant risk of injury on the lumbar spine.

Duration of inter-lift periods is a variable that addresses the cumulative nature of low back injury. Repetitive loading with shorter recovery time may cause changes in the integrity of the intervertebral disc as well as changes in the ability of the vertebral endplates to nourish the disc.(37–40) Cumulative effects of repetitive muscle activation include muscle fatigue and inflammatory responses.(41–44) Shorter periods between lifts not only indicates greater repetitive loading but also suggests an increase in the cumulative loading experienced by the spine.

The surrogate model, while showing weaker sensitivity, shows very strong specificity. In addition to the inter-lift period used in the previous models, this two-variable model used the mean of the peak static load moments. In theory these could be obtained by measuring horizontal reach distances with a tape measure and by obtaining object weights with a scale or from inventory data. One must recognize, however, that measurement errors experienced using a tape measure may be significant. Marras et al.(15) reported mean absolute errors of 10.9 cm (SD = 5.8 cm) when comparing moment arms obtained with a tape measure vs. those obtained with an electromagnetic tracking system. The tradeoff with regard to sensitivity and specificity indicates that relative to assessments performed with the full instrumentation, work assessments using the surrogate model may misclassify more of the high-risk jobs as low-risk jobs but will be unlikely to classify low-risk jobs as high-risk jobs. Therefore, when practitioners use the surrogate model and it indicates a job is high risk, it should be a priority with regard to intervention efforts, as it is unlikely that it is a misclassified low-risk job. However, practitioners using this approach should not rely on this surrogate approach to catch all high-risk jobs because of the lower sensitivity.

All of the analyses in this article are based on the injury rates determined from the OSHA 300 injury logs. Clearly, many factors affect the reporting of injuries, including organizational factors, would be inconsistent across the different facilities incorporated in this study. Nevertheless, consistent with the NRC review,(19) biomechanical variables were predictive of this outcome variable. A longitudinal component of this same investigation focused on quantifying change in kinematic back function in the employees in these jobs.(45) Work assessment variables that predicted significant degradation of kinematic function in a multivariate model included (1) the dynamic resultant sagittal bending load moment, (2) the lateral trunk velocity, and (3) the timing of the maximum dynamic asymmetric load moment during the lift. Only one of these variables, the resultant sagittal bending load moment, showed significant univariate odds ratios when predicting the injury rate classifications based on the OSHA recordable data (Tables II and III). This one significant variable was not used in the current model predicting OSHA risk group classifications as other variables combined to produce a more sensitive and specific model. When comparing the types of variables selected for the two different outcome models, the kinematic function model incorporated a load moment term that can, by its definition, include push or pull forces as well load moments incurred during lifting and lowering and, therefore, it was similar to the mean of the peak dynamic transverse plane load moments, although the latter included peak moments outside the sagittal plane. The lateral velocity and the load moment timing variables in the kinematic function model did not have analogous counterparts in the model for recordable injuries. To us this suggests that that kinematic functional impairment represents a different manifestation of the injury process, perhaps occurring earlier in the temporal progression of back injuries, prior to injury reporting, as modeled by Ferguson and Marras.(46)

There are several limitations in this project. First, because the Moment Monitor was designed to use the pin grippers on the handles to pick up loads, certain types of products such as non-boxed items, bottles of water, beverage cases, and some bulky items could not be moved with these handles and therefore could not be represented in the database. In some distribution centers, loads were carried in plastic totes. While special adaptors were designed for the Moment Monitor handles so they could be used with totes, no adaptors were created for these other varied products. Second, we also recognize that the lifting style of the workers may have slightly changed by wearing Moment Monitor and lifting with the pin-gripper handles, thereby making the models equipment dependent. Nevertheless, the analysis and models still provide quantitative indicators showing which factors are important for describing low back injury risk in distribution center jobs. Third, because jobs were the unit of analysis, the sample size was limited, which, in turn, limited the number of variables that could be used in the multivariate logistic regression models.

CONCLUSIONS

The Moment Monitor has allowed us to quantify the exposure to biomechanical and temporal risk factors associated with low back injury risk in distribution center jobs requiring manual handling of materials. Several variables that could be used to characterize the load exposure were indicative of back injury risk, including static and dynamic load moments and horizontal push/pull forces. The presented multivariate model, which has very good sensitivity and specificity, comprised a load moment variable, a variable indicating the exposure to push/pull forces, and a variable characterizing the time between lifts. Moreover, while compromising on the sensitivity, a surrogate model that does not require the instrumentation was also found to be predictive of back injury risk. Both models have the potential to help distribution center operations assess their back injury risk.

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