SPINE Volume 18, Number 5, pp 617–628

The Role of Dynamic Three-Dimensional Trunk Motion in Occupationally-Related Low Back Disorders

The Effects of Workplace Factors, Trunk Position, and Trunk Motion Characteristics on Risk of Injury

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Current ergonomic techniques for controlling the risk of occupationally-related low back disorder consist of static assessments of spinal loading during lifting activities. This may be problematic because several biomechanical models and epidemiologic studies suggest that the dynamic characteristics of a lift increase spine loading and the risk of occupational low back disorder. It has been difficult to include this motion information in workplace assessments because the speed at which trunk motion becomes dangerous has not been determined. An *in vivo* study was performed to assess the contribution of three-dimensional dynamic trunk motions to the risk of low back disorder during occupational lifting in industry. More than 400 repetitive industrial lifting jobs were studied in 48 varied industries. Existing medical and injury records in these industries were examined so that specific jobs historically categorized as either high-risk or low-risk for reported occupationally-related low back disorder could be identified. A triaxial electrogoniometer was worn by workers and documented the three-dimensional angular position, velocity, and acceleration characteristics of the lumbar spine while workers lifted in these high-risk or low-risk jobs. Workplace and individual characteristics were also documented for each of the repetitive lifting tasks. A multiple logistic regression model was developed, based on biomechanical plausibility, and indicated that a combination of five trunk motion and workplace factors distinguished between high and low risk of occupationally-related low back disorder risk well (odds ratio: 10.7). These factors included 1) lifting frequency, 2) load moment, 3) trunk lateral velocity, 4) trunk twisting velocity, and 5) the trunk sagittal angle. This analysis implies that by suitably varying these five factors observed during the lift collectively, the odds of high-risk group membership may decrease by almost 11 times. The predictive power of this model was found to be more than three times greater than that of current lifting guidelines. This study, though not proving causality, indicates an association between the biomechanical factors and low back disorder risk. This model could be used as a quantitative, objective measure to design the workplace so that the risk of occupationally-related low back disorder is minimized.
[Key words: trunk motion, lifting, ergonomics, low back disorder risk]

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Accepted October 21, 1992.

It has been known for some time that the risk of low back disorder (LBD) is associated with industrial work.[2,3,28,55,59,64,77] In particular, manual materials handling (MMH) activities, specifically lifting, dominate occupationally related LBD risk.[10,77,79,82,83] Biomechanical and epidemiologic studies of MMH tasks have identified work intensity,[13–18,23,29,38,54,56,62,68] static work postures,[26,31,38,40] frequent bending and twisting,[2,27,30,78,80,81] lifting, pushing or pulling,[10,16,26–28,38–40,54] and repetition[11,21,27,57,61,65,84] as occupational risk factors associated with LBD. However, it is also apparent that there are also conflicting findings within the literature.[10,28,36,60,66] Furthermore, the literature demonstrates that we are unable discriminate well between jobs that place workers at high or low risk of LBD. We do not know, quantitatively, how much exposure to a risk factor or combination of risk factors would alter the risk of occupationally-related LBD.

Andersson[3] suggests that the lack of association between workplace factors and risk may be attributable to the existence of confounding factors. Hence, there may be important causal factors that have been overlooked. There is a significant amount of laboratory evidence[20,35,42–52] that suggests that one of these overlooked causal factors may be trunk motions experienced by the worker. The data reported by Bigos et al[10] suggests that the risk of LBD is associated with dynamic lifting. However, this factor has never been explored in any in vivo industrial studies. Therefore, the objective of this study is to determine quantitatively and under *in vivo* conditions whether dynamic trunk motions along with the previously mentioned risk factors may better describe the risk of LBD in repetitive MMH.

■ Methods

Approach. This study involved an industrial surveillance of the trunk motions and workplace factors involved in high- and low-risk repetitive MMH tasks. The approach used in this phase of the project was to 1) identify industries involved with repetitive MMH work; 2) examine the company medical records as well as the health and safety records to identify those repetitive MMH jobs that were associated, historically, with either a high or low risk of occupationally-related LBD; 3) quantitatively monitor the trunk motions and workplace factors associated with each of these jobs; and 4) evaluate the data to determine which combination of trunk motion and workplace factors was most closely associated with LBD risk.

Data Collection. To collect information about trunk postures and movements, a method of examining three-dimensional motions of the trunk in the industrial workplace was needed. A major problem in measuring the dynamic, three-dimensional components of the trunk is that it is difficult to monitor and record such actions in the workplace. Video-based computer motion analysis systems are used for this purpose, but they are expensive and often technically unable to monitor accurately a worker under typical work conditions.[32]

A system called the lumbar motion monitor (LMM) was developed in our laboratory for the purpose of documenting the three-dimensional components of trunk motion in the work environment. The LMM is a triaxial electrogoniometer capable of assessing the instantaneous position of the thoracolumbar spine in three-dimensional space and is shown in Figure 1. The LMM was designed to be essentially an exoskeleton of the spine, which tracks position, velocity, and acceleration. The design, calibration, and accuracy of the LMM has been reported elsewhere.[41]

During data collection in industry the LMM signals were sampled at 60 Hz via an analog-to-digital converter and a portable 386-based microcomputer. The data were further processed in the laboratory to determine position, velocity, and acceleration of the trunk as a function of time in the sagittal, frontal (lateral), and transverse (axial twisting) planes of the body.

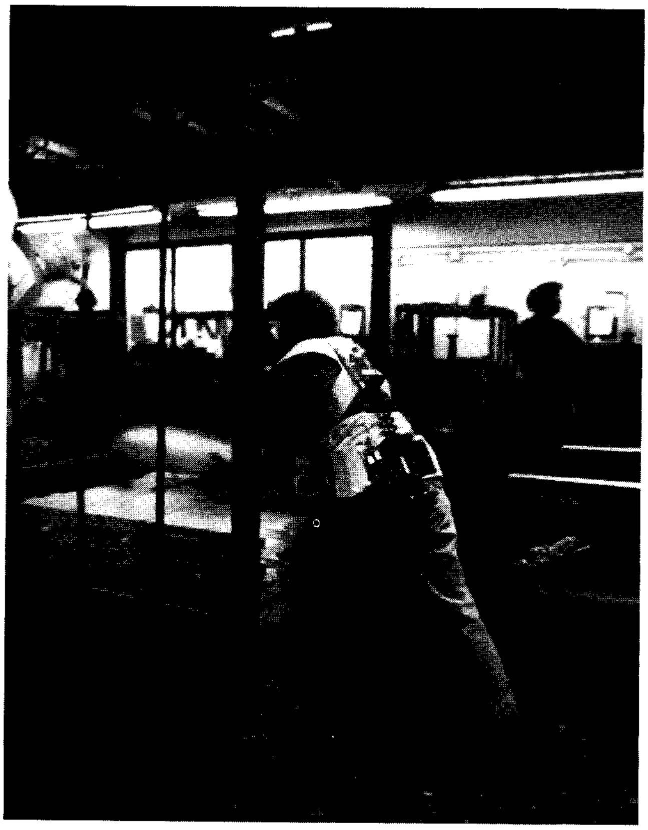

Figure 1. The lumbar motion monitor worn by a worker performing an industrial manual materials handling task.

Study Design. This study was a cross-sectional study of 403 industrial jobs from 48 manufacturing companies throughout the midwestern United States. Only repetitive jobs without job rotation were used in this study. This was necessary to prevent the confounding effects created by alternate jobs. Jobs examined in this study were divided into two groups, high and low risk of LBD, based on examination of the injury and medical records. Whenever possible, company medical reports were used to categorize risk. In some cases only injury logs (OSHA 200 logs) were available. The outcome measure (LBD risk) derived from these medical and injury records consisted of the normalized rate of reported occupationally-related LBD. Incidence of reported LBD were considered regardless of whether there was any restricted or lost time associated with the incident.

Thus, the independent variable in this study consisted of two levels of job-related LBD risk categories. Low-risk group jobs were defined as those jobs with at least three years of records showing no injuries and no turnover. Turnover is defined as the average number of workers who left a job per year. High-risk group jobs were those jobs associated with at least 12 injuries per 200,000 hours of exposure. The high-risk group category incidence rate corresponds to the 75th percentile value of the 403 jobs examined. Of the 403 jobs examined, 124 of the jobs were categorized as low-risk and 111 were categorized as high-risk. The remainder of the jobs[168] were categorized as medium-risk and were not used in most of the analyses described in this paper. The types of industries associated with the high and low-risk data base are shown in Table 1.

The dependent variables in this study consisted of workplace, individual, and trunk motion characteristics which were indicative of each job. The workplace and individual characteristics consisted of variables typically considered in current workplace guidelines for materials handling.[54,62] Specifically, these variables were 1) the maximum horizontal distance of the load from the spine; 2) the weight of the object lifted; 3) the height of the load at the origin of the lift; 4) the height of the load at the destination of the lift; 5) the frequency of lifting (lift rate); 6) the asymmetric angle of the lift (as defined by NIOSH [54]); 7) worker anthro-

Table 1. Industries Participating in the Study: Number of Jobs and Years of Experience as a Function of Group Membership and Industry Type

Manufacturer Description	No. of Companies Visited	High Risk		Low Risk	
		N	Years of Experience	N	Years of Experience
Automobile assembly	4	35	3.1 (4.6)	55	2.1 (3.1)
Chemicals and related products	4	1	2.0	6	8.2 (9.0)
Electrical and electronic equipment	3	5	6.2 (7.9)	0	—
Food processing	3	8	0.6 (0.3)	2	2.5 (2.8)
Glass production	5	0	—	2	4.5 (3.5)
Lumber and wood construction	1	2	2.3 (2.5)	0	—
Machined products manufacturing	5	22	4.1 (3.7)	21	1.8 (2.0)
Metal fabrication	1	1	6.0	1	0.1
Miscellaneous production	1	1	10.0	0	—
Paper goods production	2	2	2.5 (2.1)	1	14.0
Printing and publishing	5	2	1.2 (0.4)	2	0.5 (0.5)
Rubber and plastics production	7	3	12.3 (14.6)	11	8.1 (7.8)
Truck assembly	2	8	2.7 (3.6)	9	4.0 (3.4)
Vehicle parts/accessory assembly	5	21	4.2 (5.3)	14	5.1 (4.4)
Total	48	111	3.7 (5.0)	124	3.5 (4.7)

Values are means (with SD in parentheses).

pometry (12 measures); 8) worker injury history; and 9) worker satisfaction.

Trunk motion characteristics were those variables obtained from the LMM. These variables consisted of the trunk angular position, velocity, and acceleration characteristics (i.e., means, ranges, maximums, minimums, etc.) in each of the cardinal planes. Figure 2 indicates graphically how the various trunk motion characteristics were defined. Selected trunk motion factors along with selected workplace factors were used to develop a quantitative model of occupational risk factors.

Industrial Surveillance Protocol. Initially, data about worker health, employment history, and anthropometry were collected. Next, the worker was fitted with an LMM. A baseline reading from the LMM was then taken, while the individual stood erect and rigid. The subject then was asked to return to work and wore the LMM for at least ten job cycles. Thus, the length of time the subject wore the monitor depended upon the cycle time of the job. Monitoring of back motion was initiated as the subject began the MMH task and concluded when the subject completed the task. Extraneous activities not involving MMH were not monitored.

Analysis. Several types of analyses were performed. First, to determine how much the trunk motion and workplace measures varied from cycle to-cycle within a job, components of variance and intraclass correlation coefficients (ICCs) were extracted from a random effects analysis of variance.[53] Second, the relationship of each trunk motion and workplace variable to the risk groups was examined. This analysis included descriptive statistics as well as a simple logistic regression model fit for each variable.[24] The fitted logistic regression provides an equation that predicts the probability of high-risk LBD group membership as a function of the variable considered. Each job was weighted proportionally to the number of person-hours from which the injury and turnover rates were derived. Because the variables have very different scales, a useful summary of the fitted model is an odds ratio. The odds of LBD is defined as the ratio of the probability that a LBD occurs (probability of being in the high-risk LBD group) to the probability that LBD does not occur (probability of being in the low-risk LBD group).

Third, multiple logistic regression was used to predict the probability of high-risk group membership as a function of the values of several workplace and trunk motion factors. This type of analysis was used because the dichotomous risk classification is more relevant to workplaces than the exact values of injury rate and turnover. In addition, the descriptive statistics of the injury rates showed that this variable was so skewed that ordinary regression analyses using injury rate would not be appropriate. A multiple logistic regression model relies on the hypothesis that the logarithm of the odds that a job is high-risk is a linear function of some specific biomechanical variables. There is

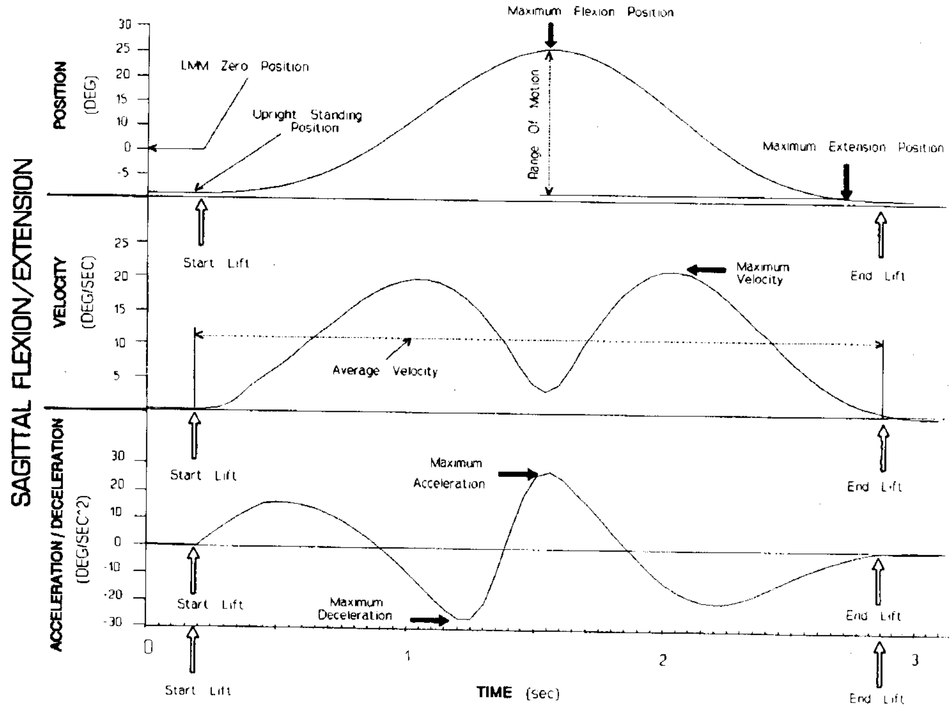

Figure 2. Definitions of trunk motion characteristics used in this study.

evidence to suggest that combinations of biomechanical factors increase disc fiber strain in an approximate linear manner.[12] A five-variable model incorporating the trunk motion and workplace factors was developed and further refined after examining a series of stepwise logistic regression models (containing different variables, e.g. velocity, acceleration) fitted to several intermediate data sets. The model was selected for the statistical importance of the predictors (deviance and Wald tests) and for biomechanical plausibility. The model variables remained consistent when tested with the various intermediate data sets. The empirical stability of the model was checked by predicting the classification of 100 jobs based on the preliminary model.

Results

Repeatability of Job Motions

The data were initially examined to determine whether the trunk motions were repeatable. This analysis indicated that the ICCs ranged from 0.49 to 0.78. Thus, generally, more than half of the variation was attributable to the job. Other analyses verified that a multiplicative model of variation gave similar ICCs. Hence, trunk motions were dictated largely by the design of the task and repetitive trials resulted in motions that were fairly similar.

Risk Group Descriptions

Table 2 shows the descriptive statistics for the high and low-risk groups. Important features of this table are:

1. The load weights and subsequent moments were, on average, much lower for the low-risk group; however, the standard deviations of the box weights are large compared to the means, so there is substantial overlap. Thus, the magnitude alone of the load imposed on the spine may not discriminate well between the two groups.
2. Comparison of the motion variables shows that there are differences between the two groups. In particular, if one compares the means and standard deviations for each of the trunk motion factors, it is apparent that the velocity factor exhibits the least overlap between risk groups. This indicates that this variable would be expected to show the greatest separation between the low- and high-risk groups.

Two sample *t* tests were used to determine which of the dependent variables were significantly different from each other in the jobs that were associated with occupational LBD compared to those jobs that were not associated with a LBD, and are shown in Table 2. This analysis indicated that the velocity trunk motion components were the only trunk motion factors that were consistently different between risk groups in all planes.

Risk Prediction

The goal of this study was to determine what trunk loading factors, or combination of factors, were associated with occupationally related LBD risk group membership. Logistic regressions were performed to determine if any single variable could distinguish jobs associated with high-risk group membership from those that were not. Table 3 shows the results of this analysis for the various trunk motion and workplace

Table 2. Descriptive and t Statistics of the Workplace and Trunk Motion Factors in Each of the Risk Groups

Factors	High Risk (N = 111)				Low Risk (N = 124)				
	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum	Statistics t
WORKPLACE FACTORS									
Lift rate (lifts/hr)	175.89	8.65	15.30	900.00	118.83	169.09	5.40	1500.00	2.1*
Vertical load location at origin (m)	1.00	0.21	0.38	1.80	1.05	0.27	0.18	2.18	1.4
Vertical load location at destination (m)	1.04	0.22	0.55	1.79	1.15	0.26	0.25	1.88	3.2†
Vertical distance traveled by load (m)	0.23	0.17	0.00	0.76	0.25	0.22	0.00	1.04	0.8
Average weight handled (N)	84.74	79.39	0.45	423.61	29.30	48.87	0.45	280.92	6.4†
Maximum weight handled (N)	104.36	88.81	0.45	423.61	37.15	60.83	0.45	325.51	6.7†
Average horizontal distance between load and L5–S1 (N)	0.66	0.12	0.30	0.99	0.61	0.14	0.33	1.12	2.5*
Maximum horizontal distance between load and L5–S1 (N)	0.76	0.17	0.38	1.24	0.67	0.19	0.33	1.17	3.7†
Average moment (Nm)	55.26	51.41	0.16	258.23	17.70	29.18	0.17	150.72	6.8†
Maximum moment (Nm)	73.65	60.65	0.19	275.90	23.64	38.62	0.17	198.21	7.4†
Job satisfaction	5.96	2.26	1.00	10.00	7.28	1.95	1.00	10.00	4.7†
TRUNK MOTION FACTORS									
Sagittal Plane									
Maximum extension position (°)	-8.30	9.10	-30.82	18.96	-10.19	10.58	-30.00	33.12	3.5†
Maximum flexion position (°)	17.85	16.63	-13.96	45.00	10.37	16.02	-25.23	45.00	1.5
Range of motion (°)	31.50	15.67	7.50	75.00	23.82	14.22	3.99	67.74	3.8†
Average velocity (°/sec)	11.74	8.14	3.27	48.88	6.55	4.28	1.40	35.73	6.0†
Maximum velocity (°/sec)	55.00	38.23	14.20	207.55	38.69	26.52	9.02	193.29	3.7†
Maximum acceleration (°/sec²)	316.73	224.57	80.61	1341.92	226.04	173.88	59.1	1120.10	4.2†
Maximum deceleration (°/sec²)	-92.45	63.55	-514.08	-18.45	-83.32	47.71	-227.12	-4.57	1.2
Lateral Plane									
Maximum left bend (°)	-1.47	6.02	-16.80	24.49	-2.54	5.46	-23.80	13.96	1.4
Maximum right bend (°)	15.60	7.61	3.65	43.11	13.24	6.32	0.34	34.14	2.6*
Range of motion (°)	24.44	9.77	7.10	47.54	21.59	10.34	5.42	62.41	2.2*
Average velocity (°/sec)	10.28	4.54	3.12	33.11	7.15	3.16	2.13	18.86	6.1†
Maximum velocity (°/sec)	46.36	19.12	13.51	119.94	35.45	12.88	11.97	76.25	4.9†
Maximum acceleration (°/sec²)	301.41	166.69	82.64	1030.29	229.29	90.9	66.72	495.88	4.1†
Maximum deceleration (°/sec²)	-103.65	60.31	-376.75	0.00	-106.20	58.27	-294.83	0.00	0.3
Twisting Plane									
Maximum left twist (°)	1.21	9.08	-27.56	29.54	-1.92	5.36	-30.00	11.44	3.2†
Maximum right twist (°)	13.95	8.69	-13.45	30.00	10.83	6.08	-11.20	30.00	2.2*
Range of motion (°)	20.71	10.61	3.28	53.30	17.08	8.13	1.74	38.59	2.9†
Average velocity (°/sec)	8.71	6.61	1.02	34.77	5.44	3.19	0.66	17.44	3.8†
Maximum velocity (°/sec)	46.36	25.61	8.06	136.72	38.04	17.51	5.93	91.97	4.7*
Maximum acceleration (°/sec²)	304.55	175.31	54.48	853.93	269.49	146.65	44.17	940.27	2.9†
Maximum deceleration (°/sec²)	-88.52	70.30	-428.94	-5.84	-100.32	72.40	-325.93	-2.74	1.6*

*Significant at $\alpha \leq 0.05$ (two-sided). Significant at $\alpha \leq 0.01$ (two-sided).

factors. This table shows that there are few factors which distinguish well between the high- and low-risk groups. Many of these variables were statistically significant. However, practically, the odds ratios were fairly low and showed that few of the individual variables discriminate well between high and low risk jobs. The most powerful single variable was maximum moment, which yielded an odds ratio of 5.17.

Of the trunk motion factors it is notable that, within each plane, the velocity variables generally produced greater odds ratios than maximum or minimum position, range of motion, or acceleration. This indicates that velocity was the strongest predictor of risk among the trunk motion factors. It is notable that other than load moment, sagittal velocity produced the greatest odds ratio (3.33). Thus, this variable is the best single trunk motion variable for discriminating between risk groups.

A multiple logistic regression model was selected to indicate risk group membership based upon biomechanical plausibility. Table 4 shows the multiple logistic regression model selected. It can be inferred from the estimated probabilities of LBD that by suitably varying all five measures (maximum load moment, maximum lateral velocity, average twisting velocity, lifting frequency, and the maximum sagittal trunk angle) observed during the lift collectively, the odds of high-risk group membership may decrease by almost *eleven times* (odds ratio, 10.7).

Other multiple logistic regression models were tested (not shown here) to investigate whether trunk range of motion, extreme trunk position, or trunk acceleration, could be used in place of lateral or twisting velocity as measures of trunk motion. When the model was adjusted in this manner, lower odds ratios resulted. Thus, compared to other trunk motion factors, the selected trunk velocity characteristics appeared to be most sensitive to risk.

For comparison purposes a multiple logistic regression model consisting of the five factors used in the *Work Practices Guide for Manual Lifting*[54] (lift rate, box weight, moment arm, lift origin, and load distance traveled) was also tested against the data base. This model yielded an odds ratios of 3.5 when the average value of the workplace factors were used and 4.6 when the maximum values of the workplace factors were used.

It is also notable that the final risk model selected did not include sagittal velocity, a variable that by itself produced an odds ratio of 3.33. When this factor was included, no increase in odds ratio was achieved. This emphasizes the multivariate nature of the trunk motion factors. Most of the trunk motion factors were highly correlated. Thus, even though factors such as sagittal velocity were not among the five factors in the risk model, such factors were still represented through their correlation with the factors that did appear in the model. Thus, the predictive power of the model requires that all five variables be present.

Risk Assessment Benchmarks

The final goal of this study was to determine the probability of occupationally-related LBD associated with combinations of various trunk motion and workplace factors. An analysis was performed to identify the magnitude of each of the five model factors that, in combination, would result in 10% incremental increases in the probability of occupationally-related high-risk group membership. Figure 3 shows these incremental "benchmarks" for probabilities of high-risk group membership that vary from 10 to 90% risk. The horizontal lines in this figure are axes for the five model risk factors, each scaled in units that represent their risk relative to the other model factor risks. The vertical lines in this figure indicate how the multivariate vector of trunk motion and workplace factors relate to the probability of high-risk group membership. Because the five risk factors are scaled proportionally, a scaled average of these variables indicate a job's overall probability of high-risk group membership. For example, the horizontal bars on this figure indicate the quantitative levels of the five workplace and trunk motion factors and the associated high-risk probabilities observed for a particular job. The vertical arrow shows the average probability of high-risk group membership associated with these five factors. The vertical line falls upon the 34% risk indicator. [The sum of the individual logits divided by five is equal to the multivariate probability; in this example (30% + 40% + 50% + 30% + 20%)/5 = 34%.] Thus, given these workplace and trunk motion factors, the model implies that a 34 percent probability of high-risk group membership would be expected. This model also implies that levels of workplace and trunk motion factors can be "traded" to offset the effects of certain high-risk factor values.

Discussion

This work represents the first study to relate epidemiologic findings with quantitative biomechanical findings in a large and varied cross-sectional industrial database. A deliberate attempt was made to include repetitive jobs representative of a broad range of industries so that the data and risk model would be as generalizable as possible. For the first time, we have been able to quantify biomechanical factors *in vivo* during industrial work. This has provided a database that will be useful for research purposes as well as for ergonomic application purposes. There are several immediate implications of this study.

First, we have been able to identify and describe the trunk motions that are present in industry. This information has shown that there is considerable three-dimensional trunk motion occurring in most industrial tasks. These findings indicate that assumptions, such as those in current lifting guidelines,[54] of sagittally symmetric, slow, smooth lifting are not consistent with the types of motions that are experienced by the workers in the workplace.

Second, we have been able to identify key factors that are indicative of occupationally related high-risk groups. High LBD risk is identified as a function of a multivariate vector of workplace factors and trunk motion factors. Many of these factors are highly correlated. Thus, by tracking just five occupationally-related factors used in the multiple logistic regression risk model (moment, lift rate, lateral trunk velocity, sagittal trunk angle, and trunk twisting velocity), we are able to predict the probability of high-risk group membership for any repetitive job. Individually, each of these factors is unable to discriminate reliably between a high-risk situation and a low-risk situation. However, when these factors are considered in combination as a representation of a multivariate vector, the risk model is capable of predicting situations that

Table 3. Individual Odds Ratios

Factors	Coefficients	Odds Ratio	SE	95% Confidence Interval
WORKPLACE FACTORS				
Lift rate	0.00005	1.00	0.0004	0.99 – 1.01
Vertical load location at origin	-0.6748	1.02	0.5636	0.98 – 1.07
Vertical load location at destination	-1.8747	1.23*	0.5817	1.08 – 1.39
Vertical distance traveled by load	-0.8702	1.03	0.6742	0.99 – 1.07
Average weight handled	0.0152	2.76*	0.0027	1.94 – 3.93
Maximum weight handled	0.0135	3.17*	0.0022	2.19 – 4.58
Average horizontal distance between load and L5–S1	0.7808	1.01	0.8838	0.99 – 1.02
Maximum horizontal distance between load and L5–S1	1.7037	1.11*	0.6770	1.02 – 1.20
Average moment	0.0313	4.08*	0.0050	2.62 – 6.34
Maximum moment	0.0254	5.17*	0.0037	3.19 – 8.38
Job satisfaction	-0.3502	1.56*	0.0760	1.29 – 1.88
TRUNK MOTION FACTORS				
Sagittal Plane				
Maximum extension position	0.0561	1.36*	0.0144	1.17 – 1.58
Maximum flexion position	0.0391	1.60*	0.0081	1.31 – 1.93
Range of motion	0.0405	1.48*	0.0091	1.24 – 1.75
Average velocity	0.1735	3.33*	0.0314	2.17 – 5.11
Maximum velocity	0.0204	1.73*	0.0044	1.37 – 2.19
Maximum acceleration	0.0036	1.70*	0.0008	1.35 – 2.14
Maximum deceleration	-0.0035	1.04*	0.0023	0.98 – 1.09
Lateral Plane				
Maximum left bend	0.0099	1.00	0.0202	0.99 – 1.02
Maximum right bend	-0.0037	1.00	0.0186	0.99 – 1.01
Range of motion	0.0071	1.01	0.0118	0.98 – 1.03
Average velocity	0.2184	1.73*	0.0452	1.38 – 2.15
Maximum velocity	0.0441	1.55*	0.0098	1.28 – 1.87
Maximum acceleration	0.0054	1.51*	0.0013	1.24 – 1.84
Maximum deceleration	0.0017	1.01	0.0022	0.98 – 1.04
Twisting plane				
Maximum left twist	0.0758	1.21*	0.0220	1.09 – 1.35
Maximum right twist	0.0523	1.13*	0.0203	1.03 – 1.24
Range of motion	0.0298	1.08*	0.0147	1.00 – 1.16
Average velocity	0.1511	1.66*	0.0324	1.34 – 2.05
Maximum velocity	0.0202	1.17*	0.0069	1.05 – 1.31
Maximum acceleration	0.0026	1.16*	0.0009	1.05 – 1.29
Maximum deceleration	0.0014	1.01	0.0017	0.98 – 1.04

*Odds ratio significantly different from 1 ($\alpha \le 0.05$; the odds ratios were computed with weight means.

would result in a greater probability of high-risk group membership. The model has excellent predictive power and could identify a more than tenfold increase in the odds of high-risk group membership. This model also permits one to determine the effects of changing the specific values of the risk factors. In this regard, the model has immediate applicability to ergonomic design and redesign of workplaces involving MMH. However, the model now needs to be validated or tested against another group of industrial jobs. Such an effort is currently in progress.

The predictive power of this model was compared to that of a current lifting guide.[54] We constructed and tested a multiple logistic regression model based on this guide and found it was, indeed, able to predict the probability of high-risk group membership. However, inclusion of the three-dimensional motion factors improved predictability by two- to three- fold (depending upon whether average or maximum values of the workplace factors were used). Thus, future guides could enhance their usefulness by recommending the inclusion of three-dimensional trunk motion measures during MMH activities in addition to traditional workplace factors.

Third, these data can be used to help understand the conditions under which various biomechanical mechanisms operate during MMH. Because this database is the only quantitative *in vivo* industrial database of trunk motions and workplace factors that we are aware of, it can provide information about the expected *in vivo* conditions associated with trunk motion loading during work. Such information is neces-

Table 4. Multiple Logistic Regression Model

Variable	Coefficient	SE
Constant	-3.80	0.67
Lift rate	0.0014	0.0006
Average twisting velocity	0.061	0.041
Maximum moment	0.024	0.004
Maximum sagittal flexion	0.020	0.012
Maximum lateral velocity	0.036	0.014
Estimated odds ratio*	10.7	
Confidence interval	4.9–23.6	

The constant and coefficients of each factor are the estimated values that give the predicted logarithm of the odds that a job is classified as having a high risk of LBD. The estimated odds ratio is the ratio of two odds described in the text, and the confidence interval is an approximate 90% confidence interval for the odds ratio.
*The odds ratio was computed with weighted means.

sary so that biomechanical properties can be tied to realistic workplace conditions. This is becoming increasingly important in light of new findings regarding *in vivo* versus *in vitro* experimentation. Keller and associates[25] found that the viscoelastic properties of the disc *in vivo* were dramatically different than those of the disc *in vitro*. They concluded that "in the absence of normal physiologic conditions, one may not be able to predict the mechanical response of the lumbar spine." Other studies[1] have examined the relationship between *in vivo* and *in vitro* viscoelasticity but have used arbitrary situations for *in vivo* lifting conditions. Studies of disc viscoelastic properties are dependent upon information about the position and rate of loading of the spine. Therefore, the present study provides quantitative *in vivo* information about trunk movement characteristics that can be used for spine-related viscoelastic research purposes.

Fourth, this information could be used to advance trunk biomechanical modeling efforts. Biomechanical models that are sensitive to three-dimensional positions of the trunk[15,47,52,67] as well as those that are sensitive to dynamic trunk motions[20,35,47,52,63] could use these data to define the limits of trunk motion characteristics expected during work. Furthermore, *in vivo* studies of muscle and intra-abdominal pressure responses during lifting[4–7,33,42–45,49,51,56,68,69,71] could use this information to define test conditions, thereby providing valuable insight as to how the musculoskeletal system responds to realistic industrial lifting conditions.

Finally, our study must be viewed in perspective with previous industrial studies,[9] which have produced drastically different findings. The previous studies have identified many psychosocial factors as significant variables in defining work-related risk of LBD in the Boeing Company. However, the types of tasks examined in this previous study were significantly different from the types of tasks examined in the current study. The Boeing study examined aircraft assembly which is primarily a "job shop" operation. The job cycles associated with the Boeing study were

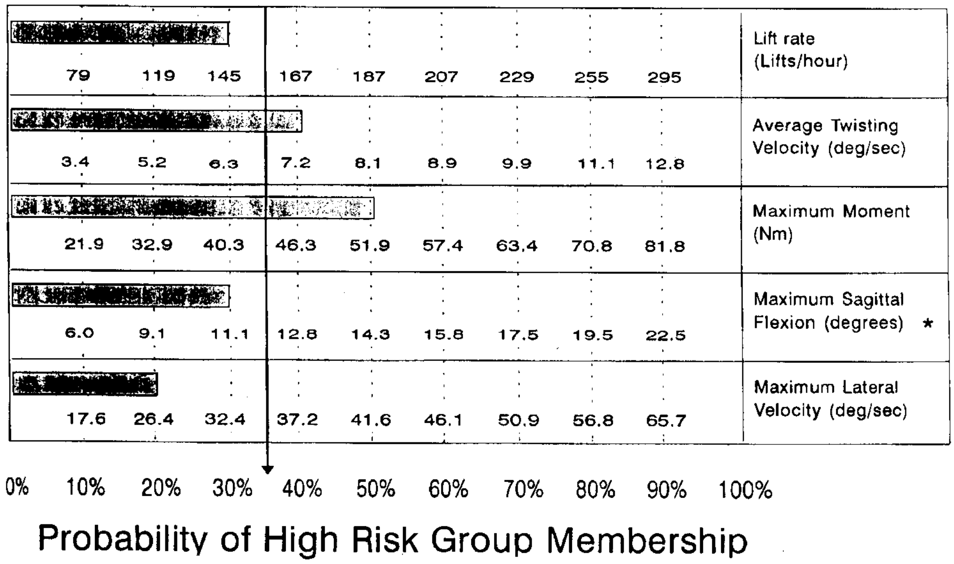

Figure 3. Relationship of overall probability of high risk group membership to the individual values of the five key risk factors. Horizontal bars indicate the value of each risk factor for a particular job. The average of the key risk factors individual probabilities (logits) indicates the overall probability of high-risk group membership. *Sagittal angle does not include resting lordotic angle.

very slow. It may take weeks or months before the same task element is repeated in such an environment. Our study, conversely, examined highly repetitive tasks, which may be more sensitive to biomechanical cumulative trauma loading of the spine structures. In addition, our study did not examine psychosocial features as did the Boeing study. Thus, the current study does not necessarily contradict the previous study. Psychosocial indicators may indeed be a better indicator of risk for varied, nonrepetitive types of work. However, when the work is highly repetitive, biomechanical indicators can provide valuable risk information.

Biomechanical Significance

From a biomechanical standpoint, this study has enabled us to determine, *in vivo* and in industrial environments, the levels of several key risk factors that place a worker at an increased risk of LBD, while simultaneously considering the interrelationship among the various risk factors. These findings are in agreement with the biomechanical and epidemiologic literature. As evidenced from this evaluation, it is difficult to evaluate job risk when workplace factors are evaluated in two-dimensional, static positions. Magnusson et al,[37] using a back monitor to evaluate static, sagittally symmetric postures, was unable to demonstrate a relationship between loading and back complaints. Shirazi-Adl et al,[76] using finite element modeling, found that the annulus was not vulnerable to rupture under pure compressive loading. Thus, these studies as well as others[2,3,40,59,73] have shown that three-dimensional factors such as shear and torsional loadings, must be considered in order to understand the loading of the spine during work.

There is also significant evidence that suggests the biomechanic relevance of three-dimensional trunk motion. Increased trunk motion during lifting could accentuate spine loading due to the reaction of the musculoskeletal system. Marras and Mirka[45] have investigated the response of the trunk musculature under isokinetic conditions which attempted to match the motion conditions observed in this study. They have shown that as trunk velocity increases the degree of trunk muscle coactivation also increases. This would tend to magnify the loading on the spine because the muscles work against one another. Trunk motion models of the spine[47,48] have also shown that as the trunk velocity increases during asymmetric lifting, significant increases in lateral shear forces occur on the spine.

Finally, the ability of the disc to tolerate strain decreases under the loading conditions described by the multiple logistic regression risk model. The lack of facet structural support that occurs while in flexed postures when the trunk is bent laterally increases disc fiber strain.[8,12,19,34,70,75] Similar reductions in fiber tolerance have been noted when lateral bending and twisting occur simultaneously while the trunk is bent forward.[22,34,58,72–74]

Limitations

Several possible study limitations must be discussed so that this information is not misused. First, this study is a cross-sectional study of MMH conditions in industry. Thus, these results do not imply a prospective causal model. These results simply indicate there is a statistically significant association or correlational between certain biomechanical factors and risk of high LBD group membership. These findings can not be used as absolute proof that these factors cause LBD. There is the possibility that underlying undocumented factors may be responsible for risk. For example, increased lateral trunk velocity may trigger slips and falls in workers with balance disturbances working in high-risk jobs. These balance disturbances (which were not explored in this study) would then be the underlying causal factor. However, in this study we did biomechanically justify the selected risk factors. Second, these results apply only to repetitive MMH types of jobs. Third, the probabilities predicted in this model indicate the probabilities of high-risk of LBD group membership. They do not indicate the risk of LBD. Finally, this study was based on the best available medical and injury records for the jobs explored. However, these records may vary in accuracy among industries and could influence model accuracy. Common problems with industrial record keeping, which could affect our findings, involve nonreporting or overreporting of injuries, missing data, misdiagnoses or incomplete data. Thus, studies based upon such data could be subject to misclassification error which could affect the study outcome.

■ Conclusions

1. Significantly large trunk range of motion, trunk velocity, and trunk accelerations in the cardinal planes are associated with industrial MMH. These motions have been quantitatively described.
2. Trunk motions patterns are primarily a function of the job environment, and to a lesser extent, cycle-to-cycle variation between lifts. Thus, these motions can be controlled by workplace design.
3. Occupationally-related low back disorder risk has been associated with a combination of five measures representing both workplace and trunk motion factors. Load moment and lifting frequency are the workplace factors. Lateral trunk velocity, twisting trunk velocity and sagittal flexion angle are the trunk motion factors. As the magnitude of each of these variables increases, the risk increases.

4. We have been able to identify the levels of workplace and trunk motion factors that, in combination, define the probability of high-risk group membership. This information could be used to design workplaces and to help understand the nature of occupationally-related LBD injury.

Acknowledgment

Partial funding for this study has been provided by the Ohio Bureau of Workers' Compensation, Division of Safety and Hygiene and the National Institute of Disability and Rehabilitation Research. The assistance of Mr. Christopher Hamrick, Mr. Larry Wright, Ms. M. L. Arboleda and Dr. Mohamed Parnianpour in the execution of this project are greatly appreciated.

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