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The Role of Complex, Simultaneous Trunk Motions in the Risk of Occupation-Related Low Back Disorders

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Study Design. Simultaneous trunk kinematic variables of industrial workers performing jobs with varying degrees of low back disorder risk were quantified, by using a three-dimensional electrogoniometer.

Objectives. To assess the distinguishing patterns of simultaneous multidimensional (complex) motion parameters of workers performing manual material handling jobs with varying degrees of low back disorder risk.

Summary of Background Data. There is significant epidemiologic and biomechanical evidence that implicates simultaneously occurring or combined motions and loading as important risk factors for low back disorder. However, the specific levels or magnitudes and patterns of these complex motions at which risk of low back disorder is increased are still unknown.

Methods. An industrial database of 126 workers and jobs was used to quantify the complex trunk motions of groups with varying degrees of low back disorder risk. Three groups, low-, medium-, and high-risk, were defined on the basis of retrospective injury records of the corresponding jobs. The jobs were further classified into five cells of weight-lift rate combinations. Within each weight-lift rate cell, the three-dimensional trunk motion patterns of workers were analyzed. Bivariate distributions and cumulative distribution functions were used to compare the simultaneous occurrence of complex dynamic motions among risk groups.

Results. High- and medium-risk groups exhibited complex trunk motion patterns involving high magnitudes of combined velocities, especially at extreme sagittal flexion; whereas the low-risk group did not. Postural trunk information alone did not provide a consistent pattern for distinguishing among risk groups.

Conclusions. Elevated levels of complex simultaneous velocity patterns were unique to groups with increased low back disorder risk. Knowledge of these complex trunk velocity patterns in combination with key workplace factors provides a more sensitive means for identifying low back disorder occupational risk factors than does mere postural information. [Key words: complex motion, ergonomics, low back disorder risk, trunk motion] **Spine 1998;23:1035–1042**

Low back disorders incurred in occupational settings are considered the most significant musculoskeletal disorders in cost and in prevalence.[1,11,24,36] Manual materials handling in general and lifting activities in particular have been implicated most often in relation to the risk of occupation-related low back disorders.[3,10,32,33,35] A wide range of individual occupational risk factors have been associated with low back disorders. These factors include work intensity,[5,6,16] static work postures,[12,14,16,17] lifting, pushing or pulling,[3,5,12,13,16–18] frequent bending and twisting,[13,14,32,34] and repetition.[12,22,26,30,37]

In more recent studies, investigators have emphasized the role of three-dimensional trunk motion characteristics in conjunction with workplace factors in relation to the risk of low back disorder.[20,21] In these "field" studies, the three-dimensional angular position, velocity, and acceleration of more than 400 repetitive industrial lifting jobs were examined, along with workplace and worker characteristics. The main finding of these studies was a "risk" model that incorporated five factors—three trunk motion factors and two workplace factors: the trunk sagittal angle, trunk lateral velocity, trunk twisting velocity, lifting frequency, and load moment. This approach is desirable compared with earlier lifting guidelines, in that it provides quantitative and objective measures to help assess and redesign the workplace so that the risk of occupation-related low back disorders is minimized.[20,21] Thus, this effort can establish how much exposure to a risk factor is too much. However, these investigators did not consider the temporal occurrence of the identified low back disorder risk factors. In other words, each risk factor was determined independent of the magnitudes of the other factors. Quantifying simultaneously occurring risk factors may be synergistic in the determination of overall risk of low back disorder.

There is significant epidemiologic and biomechanical evidence that implicates simultaneously occurring or combined motions and loading as important risk factors

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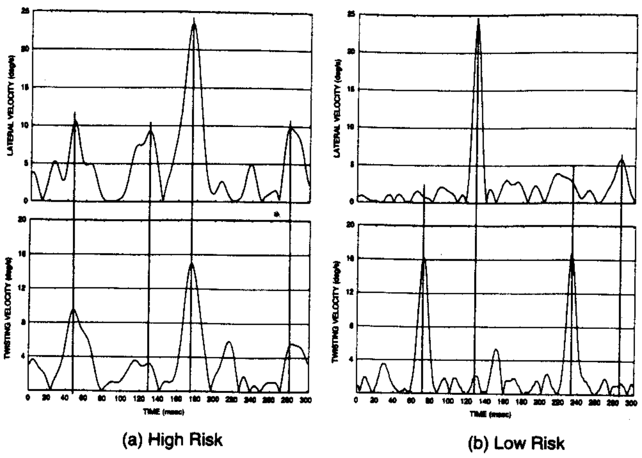


Figure 1. Simultaneous trunk lateral and twisting velocities obtained from cycles of an actual manual material handling high-risk job (A), and (B) low-risk job.

for low back disorder. Because of the nonlinear material properties and complex geometry of the spinal structure,[27–31] the response to simultaneously occurring risk factors can be expected to be more severe than the sum of the responses of individual risk factors. Investigators in several epidemiologic studies have shown that risk increases under these combined risk factor conditions. Magora[18] determined that twisting and lateral bending are significant risk factors only when occurring simultaneously with sudden movements (dynamic activities). Kelsey et al[13] indicated that occupational low back disorder risk increases in jobs involving lifting activities when the lift is combined with twisting action. Researchers in other epidemiologic studies have also indicated combined (asymmetric) motions as potential risk factors for development of low back disorders.[2,4,7,8,15,20,25,34]

In this discussion, it is suggested that combined or complex motions of the trunk may play an important role in the risk of low back disorders and can provide better insights into the mechanism of injuries associated with such disorders. However, the specific levels or magnitudes and patterns of these complex motions at which low back disorder risk is increased are unknown. Furthermore, these complex motions have not been continuously documented under occupational conditions. In Figure 1, complex motions are operationally defined, and the potential significance of these motions in identifying high-risk situations is demonstrated. The figure shows trunk motion components obtained from actual task cycles of two typical manual material handling jobs; one job had no history of low back disorders associated with it (low risk), and the other had several (greater than 12 per 200,000 man-hours) recorded back injuries (high risk).[21] For each job, the figure depicts the temporal occurrence of simultaneous magnitudes of trunk lateral and twisting velocities. If the statistical profiles of each motion variable are considered to be temporally independent, as was the case in previous reports, the parameters for both jobs are similar. For example, the magnitude of maximum lateral velocity attained in the low-risk job was very close to that of the high-risk job. However, the timing of the maximum lateral velocity value in the high-risk job occurred simultaneously with the maximum twisting velocity. Whereas, in the low-risk job, the maximum lateral velocity occurred at a distinctly different instant than did maximum twisting velocity. Similar observations can be made for submaximal values under which simultaneous high magnitudes of both velocities were occurring in the high-risk job. Therefore, based on these preliminary observations, it was anticipated that a strong correlation would be shown between risk of low back disorder and complex simultaneous motions.

Therefore, the objectives of this study were to quantify the simultaneous occurrence of complex spinal motions of workers performing manual materials handling tasks under actual industrial conditions and to assess the association of these temporally combined complex motions and workplace factors with the risk of occupation-related low back disorder.

■ Methods

Study Design. An industrial database of workers performing repetitive manual material handling jobs was used to investigate the role of complex motions in the risk of occupational low back disorders. In this study, 126 industrial jobs and workers (29 women and 97 men) were selected for in-depth analysis from a database of 403 jobs described by Marras et al.[20,21] The 126 jobs were drawn from a pool of jobs that either had reported low back incidents, or jobs that had no low back incidents and no job turnover. These types of jobs accounted for 351 jobs out of the total 403 jobs; the remaining 53 were jobs that had job turnover associated with them, with no reported low back-related incidents. The manner in which the 126 jobs were selected is detailed below. For these jobs, the continuous trunk motion patterns of the workers were analyzed to examine the simultaneous complex motion characteristics of the back as a function of risk. Based on injury and medical records, each job was classified into one of three risk groups: high, medium, and low risk of low back disorder. Risk classification was based on a combination of historical low back disorder-related incidence rates, lost days, and restricted days in a given job.[21] To isolate the role of complex trunk motion, three job-related factors (from the risk model) were controlled: sagittal angle range, lift rate (lifts per hour), and the weight of the load lifted (representing load moment). Trunk sagittal angle ranges were divided into four "windows" consisting of: 1) less than 0° (hyperextension), 2) between 0° and 15° flexion, 3) between 15° and 30° flexion, and 4) greater than 30° flexion. Patterns of combined motions were explored further as a function of combinations of lift rate and weight. Three levels of each variable were defined: high, medium, and low. The levels were based on the distributions of workplace variables determined from the 403-job database reported by Marras et al.[20,21] A low level of lift rate and weight was considered to be less than the 25th percentile value; a medium level corresponded to values ranging between the 25th and 75th percentiles; and a high level was considered to be higher than the 75th percentile. In Table 1 the

Table 1. Classification of the Selected 126 Low, Medium, and High Risk MMH Jobs Investigated in This Study by Lift Rate and Weight*

	Lift Rate (lifts/hr)					
	Low (≤50)		Medium (50–180)		High (≥180)	
Weight (N)	Group	N	Group	N	Group	N
Low (≤11)	Low risk	18 (21)	Low risk	0 (37)	Low risk	11 (11)
	Medium risk	0 (2)	Medium risk	0 (6)	Medium risk	6 (6)
	High risk	0 (1)	High risk	0 (4)	High risk	4 (4)
Medium (11–89)	Low risk	0 (10)	Low risk	12 (28)	Low risk	0 (4)
	Medium risk	0 (14)	Medium risk	12 (31)	Medium risk	0 (27)
	High risk	0 (9)	High risk	12 (29)	High risk	0 (18)
High (≥89)	Low risk	6 (6)	Low risk	0 (7)	Low risk	0 (0)
	Medium risk	12 (12)	Medium risk	0 (17)	Medium risk	11 (11)
	High risk	8 (8)	High risk	0 (14)	High risk	14 (14)

* Available number of jobs is shown in parentheses. Note that in this study, only the corner cells and the medium lift rate-medium weight cell were considered.

distribution of the original 351 jobs and the selected 126 jobs with varying risk into cells of lift rate and weight combinations is shown. In this study, only the four corner cells of Table 1, as well as the center or medium cell were considered. This approach was adopted to accentuate the extreme conditions of workplace factors, with the medium-level cell serving as a comparison. For the medium cell, representative random samples of 12 subjects each were drawn from the original medium cell's risk groups (Table 1). This was necessary for practical data reduction purposes. Note that for the low lift rate–low weight combination, there were no high- or medium-risk jobs selected. This was because of the low number of subjects in these groups (one and two, respectively). In addition, only 18 low-risk jobs were considered from the original 21 jobs in the low lift rate–low weight cell (Table 1). The three jobs that were not considered had incomplete continuous data.

The main dependent variables included the simultaneous continuous recording of combined (simultaneous) lateral and twisting velocities, and the combined lateral and twisting positions under each of the four sagittal ranges. This information was quantified for each of the risk groups under a given workplace cell, described in Table 1.

Data Collection. The details of the data collection procedure have been described in previous studies.[20,21] The three-dimensional kinematic information of industrial workers was gathered using the lumbar motion monitor developed in the Biodynamics Laboratory at The Ohio State University. The lumbar motion monitor functions as an exoskeleton that mimics the motion of the spine and provides the continuous three-dimensional position, velocity, and acceleration of the trunk during industrial work. The design, calibration, and validation of the lumbar motion monitor have been reported elsewhere.[19]

The field data collection was described in detail by Marras et al.[20,21] In summary, only repetitive manual material handling jobs were considered. Each worker performed at least 10 job cycles, of which 6 were randomly selected for analysis in this study. Continuous back motions were monitored only during task performance; therefore, extraneous activities not involving manual material handling were not monitored.

Analyses. Within a given combination of lift rate and weight (load moment) levels, bivariate distributions of combined lateral and twisting trunk velocities or combined angular positions were established for each risk group under each of the five sagittal position ranges. In Figure 2 the analysis flow associated with the observed industrial conditions is summarized. A biva-

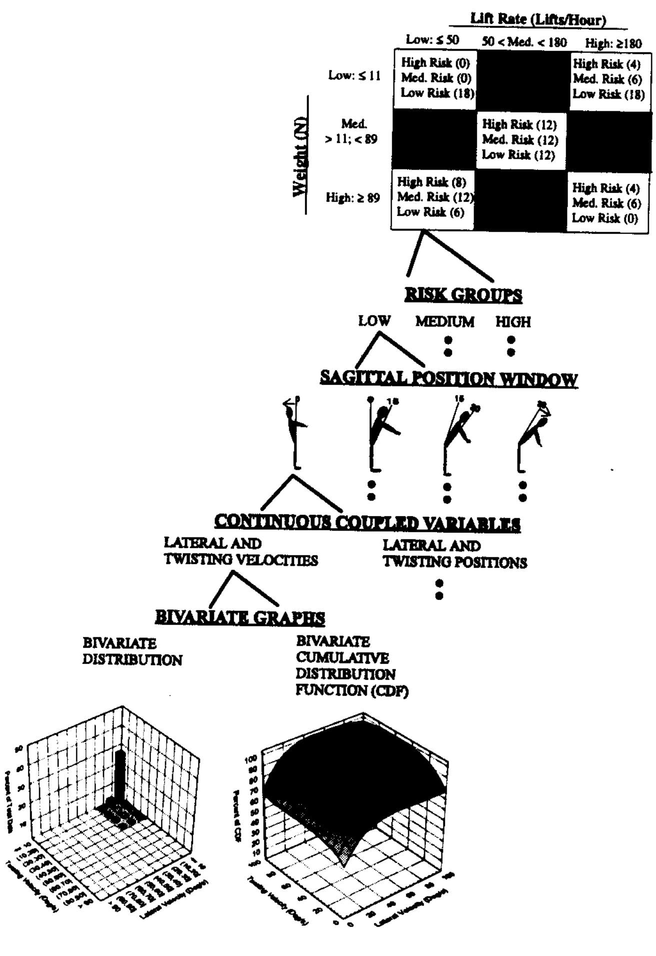


Figure 2. Typical analyses performed under each of the workplace factor combinations. Note that for illustration purposes, the sequence of analyses is shown only for complex velocities under one sample workplace cell, risk group, and sagittal window.

Table 2. Summary of the Comparison Among Risk Groups' Complex Motions Within Each of the Five Cells of Workplace Factors Combinations

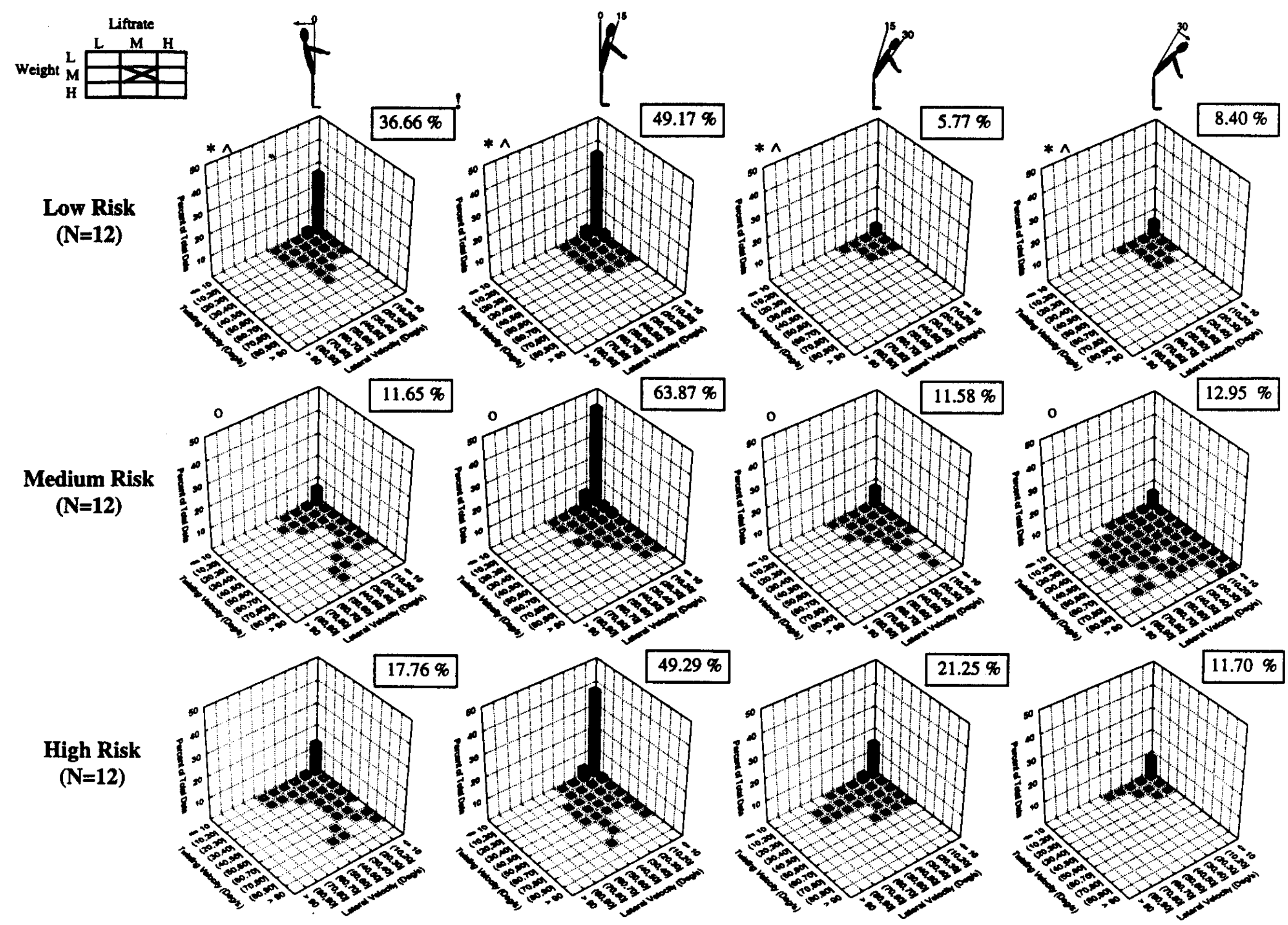
	Lift Rate (lifts/hr)		
Weight (N)	Low (≤50)	Medium (50–180)	High (≥180)
Low (≤11)	No medium or high risk jobs Complex position and velocity data concentrated at sagittal position <15° Reduced complex velocity and position magnitudes beyond 15° of sagittal flexion Lateral velocity greater than twisting velocity at extreme sagittal flexion		Complex position and velocity data concentrated at sagittal position <15° Low risk complex velocity negligible beyond 15° sagittal flexion High risk complex velocity/position concentrated below 30° sagittal flexion Complex velocity/position magnitudes were lowest of all workplace combinations (least trunk motion)
Medium (11–89)		Complex position/velocity data concentrated at sagittal position <15° Medium risk complex motion distinguished better than high risk Low risk complex position/velocity negligible beyond 15° of sagittal flexion	
High (≥89)	Complex position/velocity data concentrated at sagittal position <15° High risk had increased lateral velocity at extreme sagittal flexion Difference between high/medium and low risk groups complex velocity increased beyond 15° sagittal flexion Low risk complex position was higher than high/medium risk groups Complex velocity/position magnitudes were highest of all workplace combinations (most trunk motion)		No low risk jobs Complex position/velocity data concentrated at sagittal position <15° High risk complex velocity differ from medium only at extreme sagittal flexion No difference in complex position between high/medium at any sagittal flexion angle High risk had extreme levels of lateral velocity at extreme sagittal flexion

riate distribution represents (for a given risk group) the percentage of the total data simultaneously occurring within combined ranges of the lateral and twisting velocities or the lateral and twisting positions. Note that within a workplace cell, "total data" within each of the sagittal position windows refers to the overall continuous kinematic data (lateral and twisting velocities and positions) of all the jobs within a given risk group. In addition, to compare statistically the bivariate distributions among risk groups, bivariate cumulative distribution functions were generated for each of the bivariate velocity and position distributions within each lift rate–weight cell (Figure 2). By comparing these distributions among risk groups, it was hypothesized that insights into risky complex motions could be gained. The two-dimensional Kolmogorov–Smirnov test[9] was used to test whether the empirical bivariate distributions were statistically different among risk groups.

In addition, multiple logistic regression analysis was performed to distinguish between risk groups. Two groups were considered in this case: low-risk group (47 jobs), and combined medium- and high-risk groups (79 jobs). The measures included: two workplace variables (lift rate and maximum load moment), and one complex motion variable (average of the continuous product between sagittal position, lateral velocity, and twisting velocity).

■ Results

In Table 2, a synopsis is provided of the important findings of this study for each of the five workplace cells. The table provides several insights about trunk motion and low back disorder risk. First, most of the combined velocity and position data across all workplace factors combinations and in all three risk groups were concentrated at sagittal positions of less than 15°, indicating that workers, in general, spend most of their manual material handling activities in more or less upright postures. However, the percentage of time spent in regions beyond the 15° of sagittal flexion is considerably less in low-risk groups, when compared with the high- and medium-risk groups. Second, overall, the medium- and high-risk groups exhibited high magnitudes of complex simultaneous velocities, especially at sagittal flexion angles greater than 15°; whereas, the low-risk groups' complex velocities were concentrated at low velocity magnitudes, particularly at extreme flexion angles. Third, workplace factors seemed to alter the magnitudes and manifestation of combined motions. For example, the high lift rate–low weight conditions had the lowest magnitudes of combined motions among all the conditions investigated. This finding may indicate that when the weight of the object handled is low, workers rely less on their backs and use their upper limbs to perform their manual material handling jobs. Fourth, there was no systematic statistical difference in combined positions across all three risk groups. Beyond 15° of sagittal flexion, the high- and medium-risk groups consistently showed higher percentages of combined velocities when



!Percent of total data within a given risk group; hence, for each risk group the sum of the four percentages will be 100%

* Low Vs. medium risk; $p < 0.001$

^ Low Vs. high risk; $p < 0.001$

° Medium Vs. high risk; $p < 0.001$

Figure 3. Risk groups' bivariate lateral and twisting velocity distributions for each of the five sagittal position ranges under the *medium lift rate-medium weight* workplace cell. Within each sagittal range, statistically significant comparisons (2-D KS) among risk groups are indicated when appropriate.

compared with their corresponding low-risk groups. This phenomenon was not observed when combined positions were considered. For example, under the low lift rate–high weight combination, the low risk exhibited significantly higher percentages of combined positions at extreme sagittal flexion than the medium- and high-risk groups. Therefore, in general, complex simultaneous positions within the transverse and lateral planes could not consistently account for changes in risk as did the complex velocities in those planes. Lastly, it should be noted that, as previously reported, when workplace parameters such as object weight and lift rate are at one extreme or the other in magnitude, risk may be easily predictable.[21] For example, in the case of the low lift rate–low weight cell, there were almost no high- and medium-risk jobs (one and two jobs, respectively) identified in the Marras et al studies,[20,21] and these risk groups therefore were not investigated under this workplace condition. At the other extreme, the high lift rate–high weight cell did not have any low-risk jobs belonging to such workplace condition.

Statistical Analyses Supporting Findings

To illustrate the type of analyses performed on each risk group within a workplace cell, the complex velocities under the medium lift rate–medium weight cell were explored in detail. In Figure 3, the bivariate lateral and twisting velocity distributions are shown for each of the three risk groups under the medium lift rate-medium weight workplace combination. The distributions are presented for each of the four sagittal position windows (from hyperextension to greater than 30° of flexion). Several observations could be made in considering the information in this figure. First, in all three risk groups, most of the combined velocity data were concentrated in sagittal flexion windows of less than 15°. However, the percentages varied among the groups. For the low-risk group, 85.83% of the total time was observed under 15° of flexion; whereas, the medium- and high-risk groups had 75.5% and 67% of their total time in that region, respectively. Second, the observed magnitudes of combined lateral and twisting velocities were distinctly different among risk groups. In general, across all sagittal position windows, the low-risk group exhibited lower magnitudes of combined velocities. More important, when sagittal flexion angle exceeded 15°, not only did the low-risk group have a low percentage of its total data in this region, but also the magnitudes of combined velocities were maintained under 40°/sec. Conversely, the medium- and high-risk groups had substantial levels of combined velocities across the sagittal windows. Those high levels were maintained even at extreme sagittal flexion angles, especially in the medium risk group (combined velocities were as high as 80°/sec at sagittal range greater than 30° of flexion; Figure 3). Third, across all three risk groups, most of the data were collected at under 10°/sec combined velocities. The results of the two-dimensional Kolmogorov–Smirnov test indicated that, under each of the four sagittal flexion ranges, the bivariate distributions among risk groups (low *versus* medium, low *versus* high, and medium *versus* high) were all statistically different from each other ($P < 0.001$). These types of detailed analyses were performed in each risk group within each of the five workplace cells for complex velocities and positions (Table 2).

The multiple logistic regression model (two workplace variables and one complex motion variable) relating these workplace and trunk motion variables to risk produced an odds ratio of 14.1 (range, 7.4–27; 95% confidence interval). This represents a 3.5-point increase in the odds ratio compared with those in previous logistic models in which the magnitudes of these variables have been determined independently.[20] However, it should be noted that because the odds ratio confidence intervals of the two models overlap, this increase would not be statistically different.

■ Discussion

In previous epidemiologic studies, investigators have implicated simultaneously occurring (combined) trunk motions and loading as potential risk factors of occupation-related low back disorders and have emphasized the importance of quantifying three-dimensional factors to understand better the loads on the spine during work.[1,13,18,23] However, before this work, the levels at which these complex motions become problematic were not well understood. This industrial surveillance study has enabled investigation *in vivo* of the simultaneous complex patterns of key trunk motion parameters in conjunction with workplace factors. The results showed that there seems to be a threshold of sagittal flexion at which, if surpassed, simultaneous complex dynamic motions could be distinguished among risk groups. Below 15° of sagittal flexion, combined lateral and twisting velocities of all three risk groups exhibited similar patterns. However, even though time is spent mostly in upright positions, when workers bent more than 15°, combined lateral and twisting velocities exhibited more distinguishable patterns in each risk group. In general, the medium- and high-risk groups had elevated magnitudes of combined velocities (up to 80°/sec), whereas the low-risk groups' combined velocities were maintained at low levels (under 40°/sec). This was observed under most workplace conditions investigated, especially those with tasks involving extreme sagittal flexion angles. It was apparent that across all three risk groups, most of the data were collected at low levels of combined velocities (under 10°/sec). However, the distinguishing element among the risk groups may lie in the instances in which the dynamic activities (velocities) simultaneously reach certain magnitudes that may put the worker at risk.

Combined lateral and axial positions did not exhibit consistent patterns that could be used to distinguish among risk groups. Combined positions may in some instances provide insights about the risk of low back disorder; however, the patterns were highly variable within workplace conditions and sagittal flexion angles, making it difficult to draw definite conclusions about the role of such postural information in the risk of low back disorders. Therefore, trunk dynamics appear to be a more important factor in complex loading than does simple trunk position. This finding is in agreement with those in previous epidemiologic studies that pointed to the role of dynamic factors, especially velocity, in defining the risk of occupational low back disorder.[3,18,20,21] In addition, the current study showed that risk factors were interactive in nature. Changes in workplace conditions altered the motion patterns observed among risk groups. This finding was observed for combined velocities and positions. Furthermore, it was noted that when workplace factors were at levels less than the extreme ranges, trunk dynamics and their interaction became central to distinguishing between jobs associated with the magnitude of low back disorder risk.

When a combination of workplace parameters and simultaneous complex motion information was used, the logistic multiple regression analysis produced a significant odds ratio (14) between the low-risk group and the combined medium- and high-risk groups. This provided an improved odds ratio (however not statistically different) compared with that in previous studies in which similar factors were considered, but without the added simultaneous temporal information.[20,21] Therefore, for a given repetitive manual material handling job, assessing this combination of factors can give an indication of the odds or probability that the job shares similar patterns with jobs with increased low back disorder risk. The goal of ergonomic and workplace redesign can be directed to reduce the aforementioned probability as low as possible. Such reduction could be achieved through proper workplace redesign. This approach would guide the process of risk reduction by introducing task and/or workplace modifications in an optimal and cost-effective manner.

This study had several limitations that should be mentioned. First, the classification of jobs into risk groups depends on the quality of the medical and Occupational Safety and Health Administration records maintained by the respective companies. Misrecording and underrecording of injuries could influence the true representation of the extent of low back-related incidents. This could have resulted in misclassification of some jobs. However, this effect should be minimized because of the large size of the database. Second, the number of subjects in some of the workplace cells was limited. This may have biased some of the patterns observed under these conditions. Third, the investigators focused on assessing the association of only a selected set of workplace and motions variables with the risk of occupation-related low back disorders. Other factors (*i.e.*, psychosocial factors) may play an important role in such a correlation. Understanding the role of these potential factors and their interaction with trunk complex motions warrants further research.

Conclusions

In the biomechanical and epidemiologic literature, simultaneously occurring (complex) motion and loading of the spine have been identified as subjecting the structure to potentially risky conditions. Quantifying the simultaneous occurrence of risk factors can provide additional information about the risk imposed on the spine during work that is not obvious when the magnitudes of these risk factors are determined independently. Acknowledging the potential for further insights, this study was designed to explore, in detail, the role of simultaneous trunk motion in relation to the risk of low back disorder in occupational settings. More specifically, the results show that:

- High- and medium-risk groups exhibited unique patterns of simultaneously combined lateral and twisting velocity distributions. Unlike low-risk groups, complex and increased levels of velocities were detected in jobs with increased low back disorder risk.
- Knowledge of simultaneous complex trunk velocity patterns in combination with key workplace factors provides a more sensitive means for identifying low back disorder occupational risk factors than does mere postural information.
- Information gained in this study can help in the process of workplace redesign that is directed at reducing back disorders in industrial settings.

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