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Biomechanical risk factors for occupationally related low back disorders

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A continuing challenge for ergonomists has been to determine quantitatively the types of trunk motion and how much trunk motion contributes to the risk of occupationally-related low back disorder (LBD). It has been difficult to include this motion information in workplace assessments since 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 LBD during occupational lifting in industry. Over 400 industrial lifting jobs were studied in 48 varied industries. The medical records in these industries were examined so that specific jobs historically categorized as either low, medium, or high risk for occupationally-related LBD could be identified. A tri-axial electrogoniometer was worn by workers and documented the three-dimensional angular position, velocity, and acceleration characteristics of the lumbar spine while workers worked at these low, medium, or high risk jobs. Workplace and individual characteristics were also documented for each of the repetitive lifting tasks. A multiple logistic regression model indicated that a combination of five trunk motion and workplace factors predicted well both medium risk and high risk occupational-related LBD. These factors included lifting frequency, load moment, trunk lateral velocity, trunk twisting velocity, and trunk sagittal angle. Increases in the magnitude of these factors significantly increased the risk of LBD. The analyses have enabled us to determine the LBD risk associated with combined changes in the magnitudes of the five factors. The results indicate that by suitably varying these five factors observed during the lift collectively, the odds of high risk group membership may decrease by over ten times. These results were related to the biomechanical, ergonomic, and epidemiologic literature. The five trunk motion and workplace factors could be used as quantitative, objective measures to redesign the workplace so that the risk of occupationally-related LBD is minimized.

1. Introduction

It has been evident for some time that the risk of low back disorder (LBD) is associated with industrial work (Andersson 1981). In the United States, 30% of occupational injuries are caused by overexertion, lifting, throwing, holding, carrying, pushing, and/or pulling objects that weigh 50 pounds or less (National Safety Council 1989). About one-fifth of all workplace injuries and illnesses are back injuries, which account for up to 40% of compensation costs. Estimates of occupational LBD vary from 1% to 15% annually, depending upon occupation (Kelsey and White 1980, Snook 1989) and, over a career, can seriously affect 56% of workers (Rowe 1971).

Several reviews of the epidemiologic literature (Andersson 1981, 1991, Pope 1989) have noted that the type of work involved in an occupation is closely associated with the risk of suffering a LBD. In particular, manual materials handling (MMH) activities, specifically lifting, dominate occupationally-related LBD risk. Retrospective studies (Bigos *et al.* 1986, Spengler *et al.* 1986) of industrial injuries have identified MMH as the most common cause of LBD. It is estimated that lifting and MMH account for 50 to 75% of all back injuries (Bigos *et al.* 1986, Snook 1989, US Department of Labor 1989). Videman *et al.* (1990) also confirmed the notion that LBD risk was associated with physically heavy work, such as MMH, by examining the functional spinal units of 86 cadavers whose work and LBD history were known. They found increased degeneration in the spines of those specimens who had performed physically heavy work.

1.1 *Occupational risk factors*

Epidemiologic studies of MMH tasks have identified work intensity, static work postures, frequent bending and twisting, lifting, pushing or pulling, and repetition as occupational risk factors associated with LBD. The first and most often cited risk factor is work intensity. Physically heavy work has often been associated with an increased risk of LBD (Clemmer *et al.* 1991a, 1991b, Herrin *et al.* 1986, Klein *et al.* 1984, Magora 1970a, 1970b, Svensson and Andersson 1989). Most biomechanical studies interpret heavy work as jobs that impose large compressive forces on the spine (Chaffin 1969, Chaffin and Baker 1970, Chaffin and Muzaffer 1991, Chaffin and Park 1973, Herrin *et al.* 1986, NIOSH 1981, Ortengren *et al.* 1981, Putz-Anderson and Waters 1991, Schultz *et al.* 1982). The National Institute for Occupational Safety and Health (NIOSH) developed a lifting guide (NIOSH 1981) to assist in identifying those lifting conditions that would increase spine compression and the risk of LBD. This guide compares an estimate of disc compression with two limits. Jobs that impose less than 3400 N of compression on the disc (the action limit or AL) are considered to be safe. Jobs that impose over 6400 N of compression on the disc (maximum permissible limit or MPL) are considered hazardous. Herrin *et al.* (1986) found that musculoskeletal and over-exertion injuries were twice as likely if predicted disc compression exceeded 6800 N. However, Punnett *et al.* (1987) found that less than 3% of jobs sampled in the automobile industry imposed compressive forces greater than the NIOSH AL.

Others have interpreted heavy work relative to physical strength. Chaffin and Park (1973) as well as Herrin *et al.* (1986) found that the risk of musculoskeletal injury increased if a worker's static strength capability was exceeded. However, they were not able to identify an association with LBD specifically. Battie *et al.* (1990), when correcting for age, were not able to confirm these findings.

Several epidemiologic studies have been unable to support the association between work intensity and risk of LBD (Bigos *et al.* 1986, Kelsey and White 1980, Lockshin *et al.* 1969, Porter 1987, Sairanen *et al.* 1981). These studies found no difference in LBD prevalence between workers performing heavy versus light work. Thus, work intensity can only partially explain occupationally-related LBD risk. Andersson (1991) suggests that this lack of association between heavy work and risk may be due to the existence of confounding factors. Hence, there may be important causal factors that have been overlooked. Andersson (1991) also suggests that an additional shortcoming of epidemiologic studies is that 'the level at which physical workload becomes dangerous is not determined'.

The second risk factor, static work postures, is also often cited as an occupational LBD risk factor. Both bent over working postures (Lawrence 1955, Magora 1970a, 1970b), as well as seated working postures (Kelsey 1975) have been tied to LBD. Magora (1973) found that workers who maintained the same posture (either seated or standing) throughout the workday and those that frequently changed posture throughout the workday were at a ~~greater~~ risk of LBD. Thus, trunk position appears to be an important risk factor. Furthermore, there is evidence to suggest that motion may be associated with increased risk of LBD. Data reported by Bigos *et al.* (1986) suggest that the risk of LBD associated with dynamic lifting is three times greater than that associated with awkward static postures.

The third risk factor, frequent bending and twisting, also suggests the role of motion as a risk factor for workers. The US Department of Labor (1982) reported that bending postures are associated with 56% of LBD injuries, twisting or turning are associated with 33% of injuries, and standing is responsible for only 27% of LBD. Kelsey *et al.* (1984), Snook (1982), and Troup *et al.* (1970) found that bending and twisting were common causes of LBD. Other studies (Andersson 1981, Kyserling *et al.* 1988) have shown an increased risk of LBD with asymmetric lifting.

The fourth risk factor involves the specific MMH activities of lifting, pushing, and pulling that have been associated with an increased risk of LBD. NIOSH (1981) reports that the occupational incidence rates and lost time increase significantly when work tasks require the lifting of heavy objects, lifting from incorrect heights, and lifting frequently. They claim that lifting is the major cause of LBD. Other studies (Bigos *et al.* 1986, Kelsey 1975, Kelsey *et al.* 1984, Kelsey and White 1980, Magora 1972, Magora 1973) have also shown links between lifting and LBD risk. Studies (Chaffin and Park 1973) have shown that the risk increases by up to eight times for lifting activities compared to nonlifting activities. Several unique features of the lifting task appear to increase risk. Combinations of lifting with trunk twisting (Kelsey *et al.* 1984), lateral bending and twisting (Magora 1970a, 1970b), and sudden loading (Magora 1973) dramatically increase the risk of injury.

Finally, repetition appears to be a LBD risk factor during lifting activities. Putz-Anderson (1988) considers tasks (such as MMH) with cycle times of less than 30 s to increase the risk of a cumulative trauma disorder. Studies have demonstrated how load repetition influences fatigue fractures of the lumbar vertebrae (Brinckmann *et al.* 1988), risk of prolapsed lumbar intervertebral disc (Kelsey *et al.* 1984), and trunk strength and spine coupling patterns (Parnianpour *et al.* 1988). Wilder *et al.* (1988) have also shown that increased repetition, in the form of vibration, cause mechanical changes in the disc leading to instability of the motion segment. Studies not related to the back also indicate that repetition could lead to cumulative tendon strain (Goldstein *et al.* 1987) as well as bone density changes even during short exposures (Rubin *et al.* 1987).

These five risk factors have been identified, repeatedly, as contributing to LBD risk during MMH. However, it is apparent that there are conflicting findings within the literature (Bigos *et al.* 1986, Kelsey and White 1980, Lockshin *et al.* 1969, Porter 1987, Sairanen *et al.* 1981). Furthermore, the literature demonstrates that we are not able to discriminate well between jobs that place workers at high or low risk of LBD. It is clear that MMH will always be necessary. However, we do not know, quantitatively, how much exposure to a risk factor or combination of risk factors (i.e., how much twisting or bending) would alter the risk of occupationally-related LBD.

1.2. *Occupational biomechanics*

Much of back pain is discogenic and has a mechanical origin (Nachemson 1975). The occupational biomechanics literature has attempted to quantitatively determine these origins.

The occupational biomechanics literature has attempted to explain many of the epidemiologic findings via assessments of the loadings imposed upon the trunk structures under MMH conditions. However, many of the epidemiologic studies have been of limited use in understanding how loading is imposed upon the spine during work. These studies have been concerned with the identification of occupational risk factors in the work environment, but have not been concerned with quantitatively describing exposure to the various risks factors associated with LBD. For example, the degree of twisting or bending, on the job, that increases LBD risk has not been quantitatively documented. Therefore, it has not been possible to quantitatively determine *in vivo* the nature or combination of spine loading factors at which an increased risk of LBD occurs due to occupational exposure. Such information could generate a better understanding of how these occupational risk factors lead to LBD. This information could also be used to design workplaces so that LBD risk is minimized.

Traditionally, most biomechanical assessments of work situations have been limited to static evaluations of the trunk (Andersson *et al.* 1976a, 1974, 1976b, 1977, Chaffin 1969, Chaffin and Baker 1970, Ortengren *et al.* 1981, Schultz and Andersson 1981, Schultz *et al.* 1982, 1987). In general, they have focused primarily on the spine compression associated with lifting. Thus, these analyses have addressed, almost exclusively, the spine compression component of the work intensity risk factor. Furthermore, most of these assessments involved sagittally symmetric positions of the body. However, epidemiologic studies (Bigos *et al.* 1986, Punnett *et al.* 1987, Snook 1989) often indicate that repetitive twisting or lateral bending and lifting, even for relatively light loads, are significant risk factors for LBD. These asymmetric lifting postures are expected to increase shear and torsional loadings on the spine. Thus, biomechanical studies must explore more than just the compression component of spine loading. Only recently have biomechanical investigations attempted to determine the spine loading (Chaffin and Muzaffer 1991, Lavender *et al.* 1991, Marras and Mirka 1989, 1990, 1992, Marras and Sommerich 1991a, 1991b, McGill 1991a, 1991b) and disc tolerances associated with asymmetric loading of the trunk (Broberg 1983, Lawrence 1955, Schultz *et al.* 1979, Shirazi-Adl 1989, Sirazi-Adl *et al.* 1984).

The dynamic trunk motion components of a lift have also been associated with greater spine loading. However, historically, trunk motion components have been difficult to quantify in the workplace and, thus, have been largely ignored. Biomechanical analyses (Frievalds *et al.* 1984, Lindbeck and Arborelius 1991, McGill and Norman 1985, 1986) have shown that dynamic lifting significantly increases the predicted loading of the spine. Increased trunk velocity during lifting activities has been associated with increased trunk muscle activity and intra-abdominal pressure (Marras *et al.* 1984, 1985, Marras and Mirka 1990, 1992, Marras and Reilly 1988, Marras *et al.* 1986, McGill 1991a, 1991b), increased muscle coactivation (Marras and Mirka 1990, 1992), and increased predicted spine compression (Marras and Sommerich 1991a, 1991b, McGill and Norman 1985, 1986). Futhermore, the nature of the spine loading changes significantly. Shear and torsional loadings become more prevalent when the speed of trunk motion increases (Marras and Sommerich 1991b). Studies have also shown that lateral shear forces make the motion segment far more vulnerable to injury than compressive loading (Broberg 1983; Shirazi-Adl 1989, Shirazi-Adl *et al.*

1986, Shirazi-Adl and Drouin 1987, Shirazi-Adl *et al.* 1984). There is also *in vitro* evidence that the viscoelastic properties of the ligamentous spine may act to increase the strain on the spine during increased speed of spine motion (Adams and Hutton 1985, 1986, Hukins *et al.* 1990, Keller *et al.* 1990). Thus, we expect that a more detailed evaluation of *in vivo* occupational lifting conditions, that includes documentation of the trunk motion characteristics ~~in~~ industry, may better explain the occupational source of LBD.

This brief review, therefore, suggests that a thorough biomechanical evaluation of *in vivo* occupational LBD risk during MMH should contain several key elements. These elements include traditional external moment loading information, three-dimensional spine positioning information, and dynamic motion characteristics of the trunk during MMH activities.

1.3. *Purpose of the study*

The goals of this study were to: (1) quantify in industry the various workplace and three-dimensional trunk motion characteristics associated with occupational MMH; (2) determine which workplace and/or trunk motion characteristics were associated with an increase in risk of occupationally-related LBD; and (3) determine quantitatively, the degree of exposure to the workplace factors, trunk motion factors, or combination of these factors that are associated with the various levels of LBD risk. In other words, we wanted to determine 'how much exposure to a risk factor (or combination of risk factors) is too much'.

2. Methods

2.1. *Approach*

This project has been performed over the past six years in three phases. The first phase of the project involves an industrial surveillance project whose objective is to determine the link between trunk motions, workplace factors, and the risk of LBD. This phase identifies, quantitatively, the exposures to trunk motions and workplace factors that are associated with high versus low risk of LBD. This effort can provide quantitative guidelines for the design of low risk workplaces. The second phase of the project involves a study of trunk musculature and intra-abdominal pressure in response to various trunk motion conditions observed in the industrial environment. This second phase is performed under controlled laboratory conditions (Marras and Mirka 1989, 1990 and 1992). Finally, the third phase of this research effort involves the development of an electromyography-driven (EMG-driven) biomechanical model that predicts the loadings imposed on the spine during these various trunk motions (Marras and Sommerich 1991a, 1991b). This provides a biomechanical rationale for workplace guidelines and suggests ergonomic interventions to reduce task demands.

This study reports only the industrial surveillance portion of the project (phase one). 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 low, medium, or high 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.

2.2. *Lumbar motion monitoring*

In order 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 accurately monitor a worker under typical work conditions (Lavender and Rajulu 1991). These systems require joint markers to be placed upon the worker that must be viewed by the video cameras at all times. In many industrial environments, these markers may not be visible by the video cameras due to machinery, equipment, assembly lines, workers, mist, poor lighting, etc. The analysis is also limited by the calibrated field of view of the camera. Jobs that require the worker to move, even a few steps, are extremely difficult to document.

Many researchers have documented trunk positions using electrogoniometers (Gracovetsky and Kary 1987, Magnusson *et al.* 1990, Nordin *et al.* 1984, Otun and Anderson 1988, Pope *et al.* 1991, Quanbury *et al.* 1986). However, many of these studies were unable to document trunk position in three-dimensional space and none have focused upon the evaluation of dynamic trunk motion characteristics. 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 an electrogoniometer capable of assessing the instantaneous position of the thoracolumbar spine in three-dimensional space. The LMM was designed to be essentially an exo-skeleton of the spine. The spine itself is guided by the posterior elements that form T-sections at each vertebrae level. The LMM design is based upon this spine guidance system. The LMM is placed in parallel with the spine and moves along with the spine during work. Figure 1 shows the LMM compared to an antomical model of the spine. This instrument is designed to be worn on the back of a worker and to track the worker's trunk motion. The T-sections are connected via wires to three potentiometers in the base of the LMM. These wires differentially change the voltage readings in the potentiometers as the instrument moves forwards, backwards, or to the sides. A thin flexible rod, placed through the junction of each T-section is connected to a fourth potentiometer. This potentiometer changes voltage as the instrument is twisted. Voltage outputs from the LMM are transmitted to an analog-to-digital converter and then to a portable 386 microcomputer.

Voltage readings from the potentiometers are converted into angular position in the cardinal planes using a regression (calibration) model ($R^2 = 0{\cdot}978$ sagittal, 0·976 lateral, 0·983 twisting). A three-dimensional reference frame was used to calibate the LMM with respect to the device's position at 225 points in three-dimensional space. The zero position of the LMM was defined at a point where the LMM's thoactic plate was in line with the pelvis plate. In the zero position, there is no forward, lateral or twisting angle. All potentiometers were calibrated in this position. Thus, when the LMM was placed upon a subject standing in an upright position, a sagittal angle of approximately 14° in hyperextension would be expected that represents the lordotic curve. Motion components were analysed using custom software. The angular velocity and acceleration were obtained through numerical differentiation. Filtering (to eliminate noise) was also performed prior to differentiation of the signal.

In order to evaluate the ability of the LMM to measure velocity and acceleration, the LMM was compared with a commercially available video-based motion evaluation system (Motion Analysis, Santa Rosa, CA). Both the LMM and the Motion Analysis

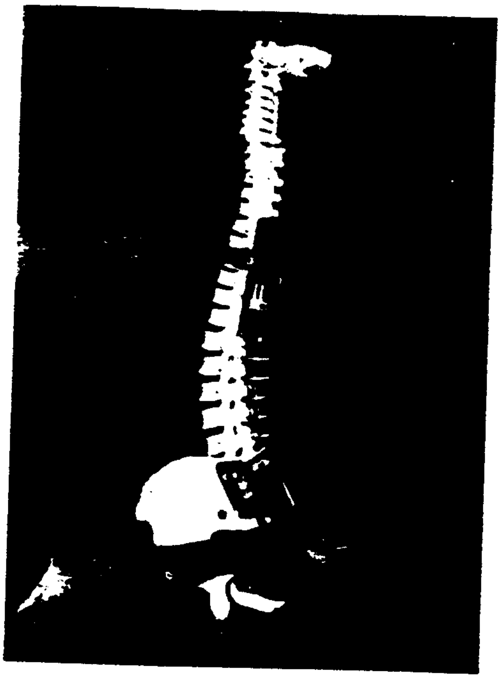

Figure 1. LMM compared to an anatomical model of the spine.

systems compute velocity and acceleration by differentiating the position signal gathered by the system. Thus, the velocity and acceleration accuracy is dependent upon the ability of the systems to accurately measure position. A calibration study (Marras *et al.* 1992) indicated that the LMM's ability to measure trunk position in three-dimensional space was much more consistent than the video-based system.

The LMM is attached via a harness to the thorax and the pelvis with a pre-moulded semi-rigid plastic material (Orthoplast). This provides two stable 'anchors', at the mid-spine (thorax) and at the pelvis. The LMM is shown on a subject in figure 2. Thus, the LMM measures the difference in spine position of primarily the lumbar spine (as a unit) relative to the pelvis. Four LMMs of varying size were constructed in order to accommodate workers with different spine lengths.

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. Two modes of LMM signal transmission were employed. When the MMH activity did not involve significant walking or carrying, the LMM signal was transmitted via a cable directly to the data acquisition computer. However, in environments where the MMH activity was performed over a large area and did require significant walking and carrying, a telemetry system was used to transmit the data from the LMM to the microcomputer. In this case, the data was multiplexed and transmitted from an antenna worn on the worker's head to receiving antennas placed around the workplace. Once received, the signals were demultiplexed and digitized by the data acquisition computer. After the data were collected, the signals were 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. These data were further processed using a 7-point moving weighted average to smooth the data and a cut-off filter of 6 Hz.

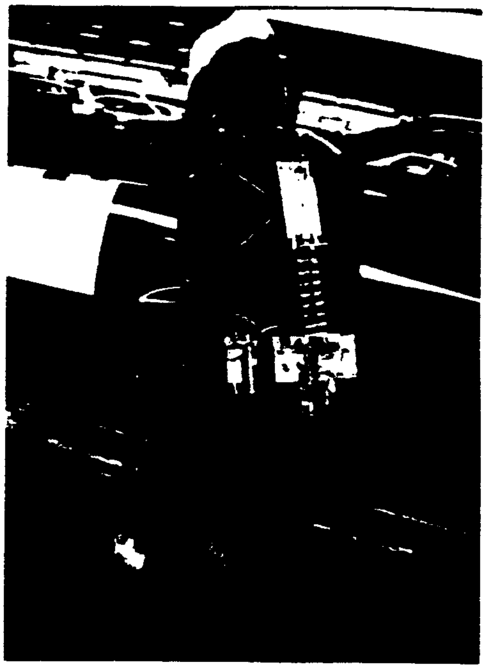

Figure 2. The LMM worn by a worker performing an industrial MMH task.

2.3 *Study design*

This study was a cross-sectional study of 403 industrial jobs from 48 manufacturing companies throughout the midwestern United States. Table 1 shows the types of industries sampled as a function of the risk grouping and work experience associated with each job category. 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 three groups, low, medium, and high risk of LBD, based upon 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.

Thus, the independent variable in this study consisted of three levels of job-related LBD risk categories based upon risk severity. Low risk jobs were defined as those jobs with at least three years of records showing no injuries and no turnover. Medium and high risk were defined based upon a risk index that weights risk as a function of severity. This risk index measure is defined in equation (1):

$$\begin{aligned}\text{RISK} = {} & \text{INC(200K)} + \text{DAYS LOST(200K)} \\ & \times 3 + \text{DAYS RESTRICTED(200K)} \times 2\end{aligned} \tag{1}$$

where

RISK is the adjusted severity index per 200,000 hours of exposure to a given job;
INC(200K) is the total number of incidents per 200,000 hours of job exposure for a given job;
DAYS LOST(200K) is the total number of days lost per 200,000 hours of exposure for a given job;
DAYS RESTRICTED(200K) is the number of days restricted per 200,000 hours of exposure for the given job.

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	Number of companies visited	Low risk		Medium risk		High risk	
		n	Years of experience Mean (Std.Dev.)	*n*	Years of experience Mean (Std.Dev.)	*n*	Years of experience Mean (Std.Dev.)
Automobile assembly	4	55	2·1 (3·1)	33	2·4 (4·3)	29	2·4 (2·9)
Chemicals and related products	4	6	8·2 (9·0)	5	7·9 (8·8)	2	2·5 (0·7)
Electrical and electronic equipment	3	0	—	16	4·3 (4·8)	12	4·2 (5·3)
Food processing	3	2	2·5 (2·8)	1	1·0 (—)	8	1·1 (1·6)
Glass production	5	2	4·5 (3·5)	9	4·7 (6·7)	4	5·1 (4·2)
Lumbar and wood construction	1	0	—	6	3·8 (4·2)	2	4·1 (5·5)
Machined products manufacturing	5	21	1·8 (2·0)	9	4·0 (3·1)	17	3·8 (4·1)
Metal fabrication	1	1	0·1 (—)	4	3·5 (2·4)	0	—
Miscellaneous production	1	0	—	0	—	1	10·0 (—)
Paper goods production	2	1	14·0 (—)	3	12·0 (9·2)	4	11·2 (11·7)
Printing and publishing	5	2	0·5 (0·5)	5	3·9 (6·3)	3	9·9 (10·2)
Rubber and plastics production	7	11	8·1 (7·8)	6	5·7 (5·4)	5	12·7 (11·7)
Truck assembly	2	9	4·0 (3·4)	6	2·3 (3·4)	3	3·2 (4·2)
Vehicle parts accessory assembly	5	14	5·1 (4·4)	23	5·1 (4·8)	11	3·2 (4·1)
Total	48	124	3·5 (4·7)	126	4·1 (5·1)	101	4·23·7 (5·7)

This measure of risk was derived to account for differences in severity between jobs that would not be indicated by incidence rate, lost or restricted days alone. Equation (1) weights jobs associated with lost time the most and jobs associated with no lost days or restricted days the least. In this manner, a measure of low back injury severity was developed. Jobs classified as high risk in this study were those jobs that had a risk index greater than the 75th percentile of the 403 jobs examined. Medium risk jobs were defined as those jobs with a risk index between the 25th and 75th percentile. Of the 403 jobs examined, 124 of the jobs were considered low risk, 126 were considered medium risk, and 101 were considered high risk. The remaining 52 jobs consisted of jobs with 0 incidence rate but a turnover greater than one. These 52 jobs were not used in most of the analyses described in this paper.

The dependent variables in this study consisted of workplace, individual, and trunk motion characteristics that were indicative of each job. The workplace and individual characteristics consisted of variables typically considered in current workplace guidelines for materials handling (NIOSH 1981, Putz-Anderson and Waters 1991). 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 origin of the lift; (4) the height of the load at the destination of the lift; (5) the frequency of lifting (liftrate); (6) the asymmetric angle of the lift (as defined by NIOSH 1991, p. 43); (7) worker anthropometry (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 3 indicates graphically how the various trunk motion characteristics were defined. The position signal was differentiated to obtain velocity. This velocity signal was rectified so that it represented the absolute value of velocity (indicating either increasing *or* decreasing speed). This absolute value of velocity was then differentiated to obtain acceleration (+) or deceleration (−). Since the absolute value of velocity was used to define acceleration/deceleration, the acceleration/deceleration signal does not indicate a vector quantity. Selected trunk motion factors along with selected workplace factors were used to develop a quantitative model of occupational risk factors.

2.4 *Industrial surveillance protocol*

Each job of interest was first reviewed to ensure that monitoring could be done safely without interfering with production. Subjects provided consent for participation and then answered a questionnaire about their health and employment history. Information about past low back strain injuries or injury symptoms in other parts of the body was collected. Subject experience with the job and a rating of job satisfaction were also recorded. Job satisfaction was measured on a ten-point Likert scale, where a rating of one indicated extreme dissatisfaction and a rating of 10 represented extreme satisfaction. Twelve anthropometric measures of gross body size and specific trunk dimensions were also collected. Anthropometric information was used for biomechanical modelling purposes and is not shown here. After the measurements were completed, the subject was fitted with a LMM. A baseline reading from the LMM was then taken, while the individual stood erect and rigid. Then the subject was asked to return to work and wore the LMM for at least ten job cycles. Thus, the length of time the subject wore

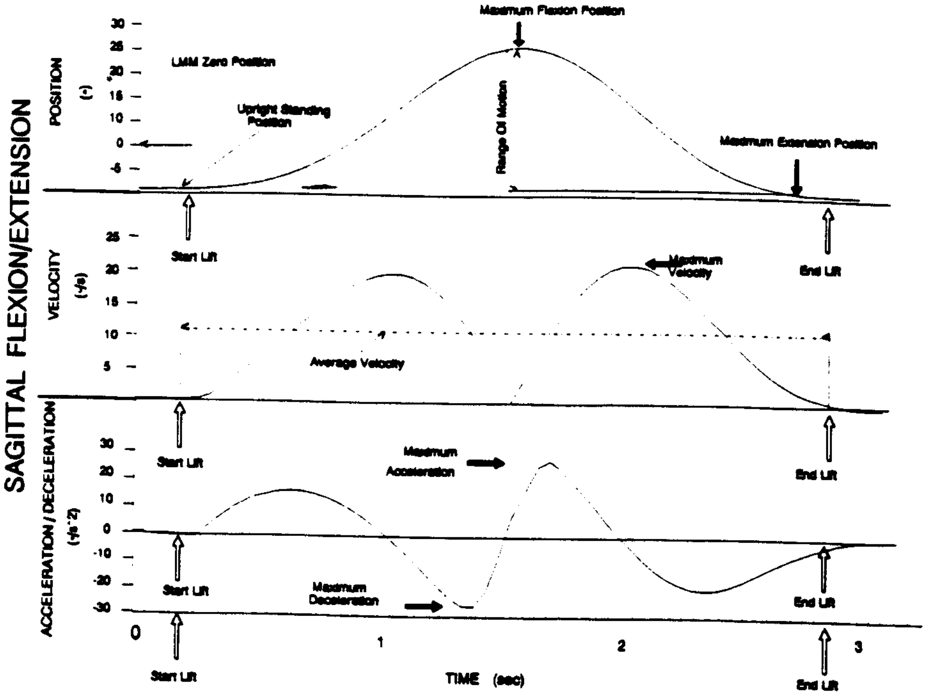

Figure 3. Definitions of trunk motion characteristics used in this study. The position signal was differentiated to obtain velocity. This velocity signal was rectified so that it represented the absolute value of velocity (indicating either increasing or decreasing speed). This absolute value of velocity was then differentiated to obtain acceleration (+) or deceleration (−). Since the absolute value of velocity was used to define acceleration/deceleration the acceleration/deceleration signal does not indicate a vector quantity.

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. Workplace characteristics as defined by NIOSH (1981) and Putz-Anderson and Waters (1991) were estimated at the workplace using a tape measure, protractor and a scale. Distance measures were made from the centre of gravity of the object lifted to the spine at the point where the object was at the farthest point from the body. Moment arm distances were determined regardless of asymmetry. Frequency of lift (liftrate) was determined from production rate throughout the day.

2.5 *Analysis*

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 (Montgomery 1991). An ICC greater than 0·5 implies that the job-to-job variation is larger than the cycle-to-cycle variation, and that the measured values are more characteristic of the jobs than they are of the cycles. An ICC of 1·00 indicates that every cycle within a job has exactly the same value, or that the variations are entirely characteristic of the jobs. Before examining combinations of the variables, the relationship of each trunk motion and workplace variable alone to the risk groups was examined. Two sample t-tests were used to determine whether the low risk LBD groups shows statistically significant differences from the medium and high risk groups. To facilitate comparison with the multiple logistic regressions described in the next paragraph, simple logistic regression models were fitted for each variable (Hosmer and Lemeshow 1989). The fitted logistic regression provides an equation that predicts the probability of high risk LBD group membership (which will be herein referred to as the probability of LBD) 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. A useful summary of the fitted model is an odds ratio because the variables have very different scales. The odds of LBD is defined as the ratio of the probability that a LBD occurs (probability of being in the medium or high risk LBD group) to the probability that LBD does not occur (probability of being in the low risk LBD group).

We used multiple logistic regression 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.

Multiple logistic regression were used to predict the probability of a LBD as a function of the values of several workplace and trunk motion factors. A multiple logistic regression model relies on the hypothesis that the logarithm of the odds that a job is high risk (or medium risk) is a linear function of some specific biomechanical variables. This is a reasonable biomechanical assumption since Broberg (1983) demonstrated how linear combinations of spine loading variables result in disc fibre strain. A five-variable model incorporating the trunk motion and workplace factors was developed. This model was 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.

Based upon the logistic regression analysis, trunk motion and workplace factor benchmarks were obtained for the various probabilities of LBD risk. Benchmarks permit graphical presentation of the way in which multiple risk factors combine to contribute to the probabilities of LBD.

3. Results

3.1. *Repeatability of motions within jobs*

The data were initially examined to determine whether the trunk motions were repeatable. This analysis is summarized in table 2. ICCs ranged from 0·49 to 0·78. Thus, generally, more than half of the variation was due to the job. (In other analyses we verified that a multiplicative model of variation gave similar ICCs.) Hence, the trunk motions were dictated largely by the design of the task and repetitive trials results in motions that were fairly similar. Therefore, computing the summary measures such as average and peak ranges, velocities and accelerations provides a value that is characteristic of a job and does not represent an artifact of the particular trials analysed.

3.2. *Description of occupational trunk motions and workplace factors*

The first goal of this study was simply to describe the various trunk motion and workplace factors observed in the industrial environment. The summary statistics in table 3 show these descriptions for all 403 jobs. Several points are worthy of mention:

Table 2. Intraclass correlation coefficient (ICC) for each motion factor for all subjects. An ICC refers to the fraction of the variance due to the job. Standard deviations are presented for between (computed over all trials) and within jobs.

Motion factors	Units	All jobs ($n = 403$)		
		Std. Dev. (Between)	Std. Dev. (Within)	ICC
Sagittal plane				
Maximum extension position	Degrees (°)	8·08	4·33	0·78
Maximum flexion position	°	12·94	9·39	0·63
Range of motion	°	11·15	8·77	0·60
Average velocity	°/s	3·36	2·99	0·51
Maximum velocity	°/s	16·84	15·65	0·49
Maximum acceleration	°/s^2	88·98	86·80	0·47
Maximum deceleration	°/s^2	84·83	79·51	0·48
Lateral plane				
Maximum left bend	°	5·55	3·89	0·64
Maximum right bend	°	5·33	4·40	0·55
Range of motion	°	7·57	4·94	0·66
Average velocity	°/s	2·60	1·91	0·62
Maximum Velocity	°/s	10·94	8·44	0·59
Maximum acceleration	°/s^2	77·03	61·90	0·57
Maximum deceleration	°/s^2	76·16	59·16	0·59
Twisting plane				
Maximum left twist	°	6·89	4·15	0·71
Maximum right twist	°	6·71	4·18	0·71
Range of motion	°	7·07	4·92	0·68
Average velocity	°/s	3·41	2·30	0·71
Maximum velocity	°/s	14·64	11·58	0·61
Maximum acceleration	°/s^2	99·76	87·68	0·56
Maximum deceleration	°/s^2	97·64	81·61	0·58

(1) the standard deviations indicate that there is a significant amount of variation associated with all factors, (2) the dynamic trunk motion values are of substantial magnitude: peak trunk velocities exceeded 200°/s and peak accelerations exceed 1600°/s^{2}, (3) the greatest range of motion was observed in the sagittal plane and the least in the transverse plane, and (4) the mean sagittal and lateral velocities were similar; however, the variation in relative velocity was much lower in the lateral plane.

Table 4 shows the descriptive statistics for the 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 often as large or larger than the means, so there is substantial overlap. Thus, the magnitude, alone, of the load imposed on the spine may not discriminate well between the groups. (2) Comparison of the motion variables shows that there are differences between the 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 the low and two other risk groups. This indicates that this parameter would be expected to show the greatest separation between the low and high risk groups. A graphical depiction of the difference in motion related factors can be found in figures 4a and 4b. Figure 4a shows actual data from a low risk job. This figure

Table 3. Descriptive statistics of workplace and trunk motion factors for all jobs (values based on the maxima of each job's trials).

Factors	Units	All jobs ($n = 403$) Mean	Std. Dev.	Minimum	Maximum
Workplace factors					
Liftrate	Lifts per hour	168·03	222·29	2·00	2500·00
Vertical load location at lift origin	Metres (m)	1·01	0·24	0·18	2·18
Vertical load location at lift destination	m	1·07	0·24	0·25	1·88
Vertical distance travelled by load	m	0·25	0·21	0·00	1·40
Average weight handled	Newtons (N)	64·25	75·63	0·45	592·69
Maximum weight handled	N	82·35	97·81	0·45	891·82
Average horizontal distance between load and L5/S1	m	0·66	0·14	0·30	1·19
Maximum horizontal distance between load and L5/S1	m	0·75	0·20	0·30	1·40
Average moment	Nm	41·81	47·76	0·16	300·42
Maximum moment	Nm	57·90	65·28	0·17	521·00
Job satisfaction	—	6·44	2·36	1·00	10·00
Trunk motion factors					
Sagittal plane					
Standing upright position	Degrees (°)	− 15·38	7·16	− 40·10	9·94
Maximum extension position	°	− 8·20	10·78	− 30·00	45·00
Maximum flexion position	°	15·68	16·93	− 25·23	45·00
Range of motion	°	28·98	16·23	3·99	75·00
Average velocity*	°/s	9·83	6·89	1·40	48·88
Maximum velocity*	°/s	49·53	33·51	9·02	207·55
Maximum acceleration	$°/s^2$	286·99	199·09	59·10	1341·92
Maximum deceleration	$°/s^2$	− 89·73	55·81	− 514·08	0·00

Lateral plane					
Maximum left bend	°	− 1·90	5·75	− 24·37	24·49
Maximum right bend	°	14·62	6·85	0·34	43·11
Range of motion	°	22·96	9·76	4·87	62·41
Average velocity*	°/s	8·96	3·96	2·13	33·11
Maximum velocity*	°/s	27·97	10·94	7·29	77·85
Maximum acceleration	°/s²	174·40	77·03	41·88	816·56
Maximum deceleration	°/s²	− 173·49	76·16	− 652·77	− 33·69
Twisting plane					
Maximum left twist	°	− 0·52	6·78	− 30·00	29·54
Maximum right twist	°	12·96	7·48	− 13·45	30·00
Range of motion	°	19·83	9·65	1·74	53·30
Average velocity*	°/s	7·63	5·64	0·66	39·87
Maximum Velocity*	°/s	45·12	24·16	3·55	185·98
Maximum acceleration	°/s²	312·47	195·33	35·14	1643·73
Maximum deceleration	°/s²	− 95·80	70·47	− 428·94	− 0·95

*All velocity figures are absolute values.

shows the position of the thorax relative to the pelvis in three-dimensional space for one cycle of an industrial task. Successive points in the plot are temporally separated by one-sixtieth of a second. Thus the more space between the points, the faster the motion. Most of the motion in this task occurs in the sagittal plane. There is motion in the other planes, but the velocity is not substantial. In constrast, figure 4b shows the same information for one cycle of a job associated with high risk of LBD. The motion in the lateral direction is faster and more apparent.

Two sample *t*-tests were used to determine which of the individual 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. Table 4 also shows the results of these tests. This table indicates that mnay variables distinguished well between the two groups. However, the velocity factors were the only trunk motion factors that were consistently different between risk groups in all planes.

3.3. *Trunk motion and workplace risk factors*

The second goal of this study was to determine which trunk loading factors, or combination of factors, were associated with increases and decreases in occupationally-related LBD. Logistic regressions were performed to determine if any single variable could distinguish jobs that were associated with LBD from those that were not. Table 5 shows the results of this analysis for the various trunk motion and workplace factors. This table shows that there are few factors that distinguish well between the risk (high or medium risk) and no risk (low risk) groups. Many of these variables were statistically significant. However, in practice, the odds ratios were fairly low and showed that few of the individual variables discriminate well between low and high or low and medium risk. The most powerful single variable was maximum moment, which yielded an odds ratio of 4·04 between low and medium risk groups.

Of the trunk motion factors it is notable that in general, within each plane, the velocity variables 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, for both the low vs. medium risk and low vs. high risk group comparisons. This indicates that this variable is the best single trunk motion variable for discriminating between risk groups.

A multiple logistic regression model was selected to indicate risk based upon biomechanical plausibility. Table 6 shows the multiple logistic regression model selected, which described the risk index well between the low and high groups as well as between the low and medium risk groups. The estimated probabilities of LBD risk imply 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 LBD (high risk LBD group membership) may decrease by over ten times (odds ratio: 10·6). Slightly more moderate but statistically significant odds ratios (6·3) were observed for the same five variables when the low risk group was compared with the medium risk group.

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

Table 4. Descriptive and *t*- statistics of the workplace and trunk motion factors in each of the risk groups.

Factors	Units	Low risk (*n* = 124) Mean	Std. Dev.	Medium risk (*n* = 126) Mean	Std. Dev.	High risk (*n* = 101) Mean	Std. Dev.	*t*-statistics Low risk Vs Medium risk	*t*-statistics Lowrisk Vs High risk
Workplace factors									
Liftrate	Lifts per hour	118·83	169·09	196·34	206·57	225·63	309·85	3·2″	3·1″
Vertical load location at lift origin	(m)	1·05	0·27	1·00	0·21	1·01	0·21	1·7	1·2
Vertical load location at lift destination	m	1·15	0·26	1·00	0·20	1·04	0·23	4·9″	3·2″
Vertical distance travelled by load	m	0·25	0·22	0·23	0·18	0·25	0·18	0·8	0·2
Average weight handled	Newtons (N)	29·30	48·87	75·00	76·88	88·40	75·43	5·6″	6·8″
Maximum weight handled	N	37·15	60·83	98·23	101·78	113·69	87·23	5·8″	7·5″
Average horizontal distance between load and L5/S1	m	0·61	0·14	0·68	0·14	0·65	0·12	4·0″	2·3″
Maximum horizontal distance between load and L5/S1	m	0·67	0·19	0·82	0·20	0·76	0·19	5·9″	3·3″
Average moment	Nm	17·70	29·18	51·40	50·80	55·45	46·81	6·4″	7·0″
Maximum moment	Nm	23·64	38·62	73·47	69·08	76·70	57·74	7·0″	7·9″
Job satisfaction	—	7·28	1·95	6·30	2·46	6·22	2·21	3·8″	3·7″
Trunk motion factors									
Sagittal plane									
Maximum extension position	°	−10·26	10·74	−6·23	11·73	−7·96	10·03	2·8″	1·6″
Maximum flexion position	°	10·37	16·02	17·61	16·17	20·03	18·16	3·5″	4·2″
Range of motion	°	23·82	14·22	30·00	16·02	33·95	16·63	3·1″	4·7″
Average velocity*	°/s	6·55	4·28	11·43	7·46	12·37	7·37	6·3″	7·0″
Maximum velocity*	°/s	38·69	26·52	53·69	36·37	59·00	36·19	3·7″	4·7″
Maximum acceleration	°/s^2	226·04	173·88	306·74	211·84	340·27	211·65	3·3″	4·3″
Maximum deceleration	°/s^2	−83·32	47·71	−79·69	49·61	−95·15	62·73	0·6	1·5

Table 4—*continued*.

Factors	Units	Low risk ($n = 124$) Mean	Low risk ($n = 124$) Std. Dev.	Medium risk ($n = 126$) Mean	Medium risk ($n = 126$) Std. Dev.	High risk ($n = 101$) Mean	High risk ($n = 101$) Std. Dev.	*t*-statistics Low risk Vs Medium risk	*t*-statistics Lowrisk Vs High risk
Lateral plane									
Maximum left bend	°	−2·54	5·46	−0·95	6·12	−1·37	5·74	2·1′	1·5
Maximum right bend	°	13·24	6·32	15·90	7·44	14·90	6·86	3·0″	1·8
Range of motion	°	21·59	10·34	23·48	9·57	23·39	9·40	1·5	1·4
Average velocity*	°/s	7·15	3·16	10·07	3·92	10·19	4·35	6·5″	5·9″
Maximum velocity*	°/s	35·45	12·88	45·14	18·97	44·58	17·47	4·7″	4·4″
Maximum acceleration	°/s²	229·29	90·9	299·62	154·64	294·82	153·06	4·4″	3·8″
Maximum deceleration	°/s²	−106·20	58·27	−100·43	73·98	−107·54	57·61	0·7	0·2
Twisting plane									
Maximum left twist	°	−1·92	5·36	−0·12	6·17	2·09	8·65	2·5′	4·1″
Maximum right twist	°	10·83	6·08	13·61	8·38	15·58	7·82	3·0″	5·0″
Range of motion	°	17·08	8·13	21·26	11·28	21·28	9·46	3·3″	3·5″
Average velocity*	°/s	5·44	3·19	9·24	6·86	8·76	6·09	5·6″	4·9″
Maximum Velocity*	°/s	38·04	17·51	48·48	27·30	49·72	27·64	3·6″	3·7″
Maximum acceleration	°/s²	269·49	146·65	341·72	233·75	320·91	191·74	2·9″	2·2′
Maximum deceleration	°/s²	−100·32	72·40	−86·18	75·08	−85·53	55·88	1·5	1·7

*All velocity figures are absolute values. ′ $\alpha \leq 0{\cdot}5$; ″ $\alpha \leq 0{\cdot}01$.

Table 5. Single workplace and motion factors odds ratios between the low and medium risk groups, and between the low and high risk groups.

Factors	Low vs. medium					Low vs. high				
	Coefficients	Odds ratio**	Standard error	95% Confidence interval		Coefficients	Odds ratio**	Standard error	95% Confidence interval	
Workplace factors										
Liftrate	0·0008	1·03	0·0007	0·97	1·10	0·00152	1·22	0·0007	1·02	1·45
Vertical load location at lift origin	−1·4163	1·07	0·8108	0·99	1·16	−0·4173	1·01	0·5033	0·98	1·05
Vertical load location at lift destination	−3·8394	1·78*	0·8480	1·40	2·28	−2·2853	1·41*	0·6103	1·20	1·68
Vertical distance travelled by load	−2·2428	1·17*	0·8362	1·05	1·31	−2·6830	1·27*	0·8135	1·10	1·47
Average weight handled	0·0103	1·61*	0·0040	1·12	2·30	0·0154	2·09*	0·0040	1·44	3·03
Maximum weight handled	0·0122	2·37*	0·0038	1·39	4·03	0·0145	2·42*	0·0033	1·64	3·58
Average horizontal distance between load and L5/S1	2·1844	1·09	1·2094	0·99	1·20	2·0072	1·08	1·0592	0·99	1·18
Maximum horizontal distance between load and L5/S1	3·0143	1·39*	0·8884	1·15	1·69	1·8076	1·13*	0·7926	1·02	1·30
Average moment	0·0239	2·23*	0·0078	1·33	3·74	0·0318	2·76*	0·0072	1·76	4·32
Maximum moment	0·0257	4·04*	0·0065	2·03	8·06	0·0273	3·32*	0·0055	2·06	5·33
Job satisfaction	−0·2348	1·325*	0·0759	1·11	1·58	−0·3065	1·48	0·0858	1·19	1·84
Trunk motion factors										
Sagittal plane										
Maximum extension position	0·0963	2·68*	0·0201	1·79	4·01	0·0430	1·19*	0·0162	1·05	1·35
Maximum flexion position	0·0355	1·38*	0·0108	1·14	1·68	0·0247	1·21*	0·0090	1·06	1·39
Range of motion	0·0131	1·04	0·0104	1·98	1·1	0·0241	1·16*	0·0103	1·03	1·31
Average velocity	0·1858	2·55*	0·0451	1·63	3·99	0·1990	2·48*	0·0456	1·65	3·72
Maximum velocity	0·0164	1·36*	0·0060	1·09	1·70	0·0192	1·34*	0·0065	1·11	1·63
Maximum acceleration	0·0030	1·49*	0·0010	1·13	1·95	0·0033	1·35*	0·0011	1·11	1·65
Maximum deceleration	0·0015	1·03	0·0026	0·92	1·15	−0·0041	1·01	0·0026	0·99	1·02

Table 5.—*continued.*

Factors	Low vs. medium					Low vs. high				
	Coefficients	Odds ratio**	Standard error	95% Confidence interval		Coefficients	Odds ratio**	Standard error	95% Confidence interval	
Lateral plane										
Maximum left bend	0·0106	1·00	0·0257	0·98	1·02	0·0138	1·01	0·0269	0·98	1·03
Maximum right bend	−0·0064	1·00	0·0201	0·98	1·01	−0·0606	1·18*	0·0224	1·05	1·34
Range of motion	−0·0156	1·02	0·0160	0·98	1·07	−0·0291	1·09	0·0149	1·00	1·18
Average velocity	0·1862	1·55*	0·0506	1·22	1·95	0·1039	1·14*	0·0471	1·02	1·28
Maximum velocity	0·0276	1.27*	0·0101	1·07	1·51	0·0138	1·04	0·0098	0·98	1·10
Maximum acceleration	0·0038	1·36*	0·0014	1·09	1·70	0·0023	1·06	0·0016	0·98	1·14
Maximum deceleration	0·0007	1·00	0·0015	0·98	1·03	0·0040	1·04	0·0030	0·98	1·10
Twisting plane										
Maximum left twist	0·1295	1·42*	0·0373	1·16	1·73	0·0922	1·47*	0·0253	1·19	1·80
Maximum right twist	0·0359	1·07	0·0219	0·98	1·16	0·1032	1·58*	0·0252	1·27	1·98
Range of motion	0·0208	1·05	0·0153	0·98	1·12	0·0309	1·08	0·0147	1·00	1·18
Average velocity	0·1087	1·60*	0·0315	1·22	2·08	0·1188	1·39*	0·0406	1·11	1·73
Maximum Velocity	0·0152	1·16*	0·0068	1·02	1·32	0·0142	1·09	0·0078	0·99	1·19
Maximum acceleration	0·0019	1·21*	0·0008	1·03	1·42	0·0005	1·01	0·0009	0·98	1·03
Maximum deceleration	0·0060	1·21*	0·0021	1·06	1·38	0·0059	1·13*	0·0025	1·02	1·26

*Odds ratio significantly different from 1 ($\alpha \leq 0.05$).

**The odds ratios in this table were computed with weighed means.

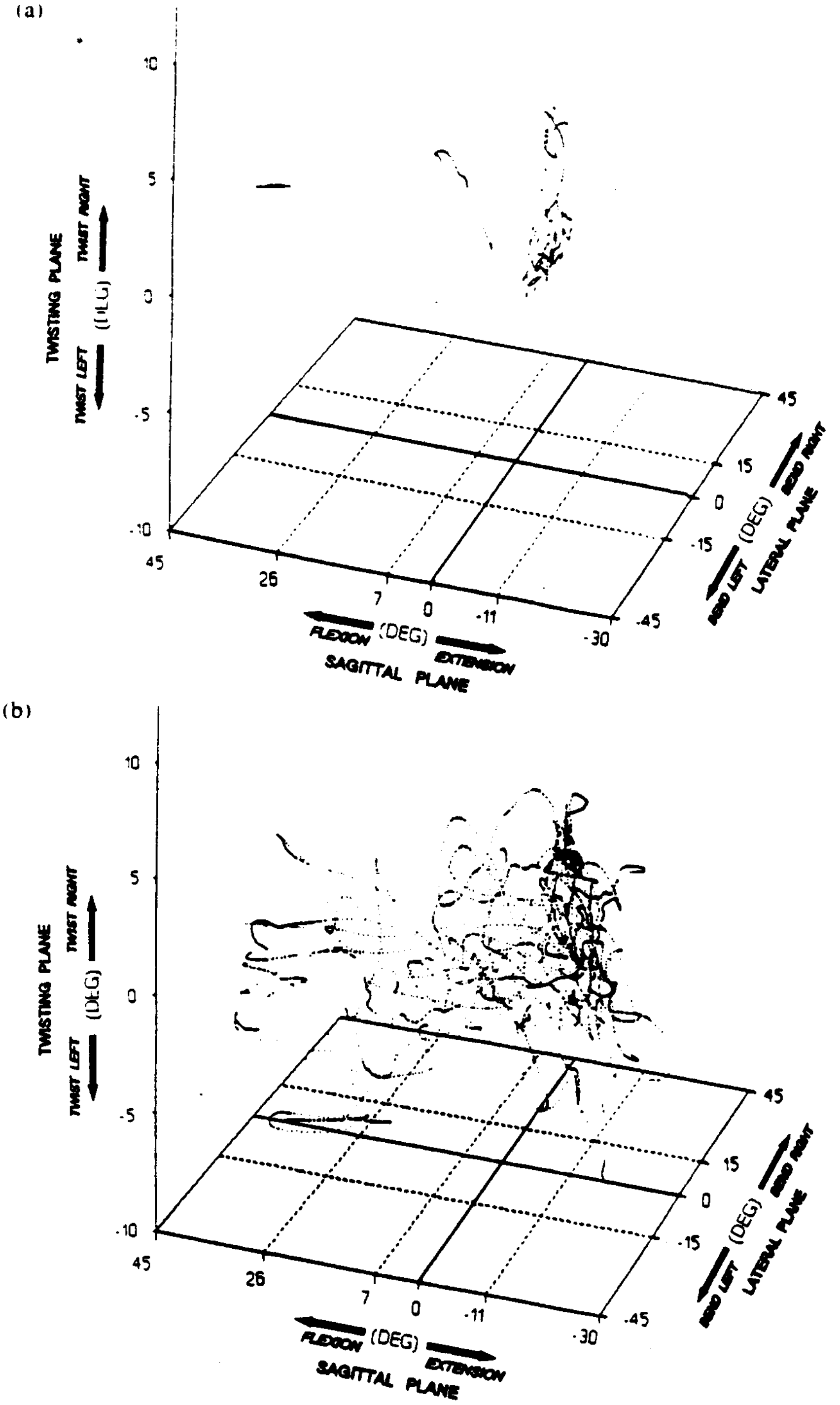

Figure 4. (a) Trunk motion position profile of the thorax relative to the pelvis in three-dimensional space collected during a low risk industrial task. (b) Trunk motion position profile of the thorax relative to the pelvis in three-dimensional space collected during a high risk industrial task.

other trunk motion factors, trunk velocity characteristics appeared to be most sensitive to risk.

It is also notable that the model selected did not include sagittal velocity, a variable that by itself produced an odds ratio of 2·48 for the low vs. high risk group comparison. 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.

3.4. *Model validity*

The empirical stability of the model was checked by predicting the classification of 100 high and low risk jobs based on the preliminary model. A discriminant function analysis indicated that the mdoel correctly predicted the classification of 87% of the low risk jobs and 78% of the high risk jobs. Further analyses involving 33 medium risk jobs indicated that this group was correctly classified 49% of the time. These jobs were most often misclassified as low risk (33%).

3.5. *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 occupationally-related LBD risk. Figure 5 shows these incremental 'benchmarks' for probabilities of occupationally-related LBD that vary from 10% to 90% risk. It is important to realize that once again, this probability represents the risk of membership in the high risk LBD group as defined in this study and is not the probability of having a LBD. The horizontal lines of 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 risk of occupationally-related LBD. Since the five risk factors are scaled proportionally, a scaled average of these variables indicates a job's overall risk of LBD injury. For example, the horizontal bars in figure 5 indicate the quantitative levels of the five workplace and trunk motion factors and the associated LBD probabilities observed for a particular job. The vertical line (arrow) shows the average risk associated with these five factors. This washed vertical line falls upon the 34% risk indicator. [The sum of the individual logits divided by five is equal to the mutlivariate 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% probability of LBD (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.

4. Discussion

These findings are unique in that this is the first study to relate epidemiological factors with quantitative biomechanical factors in a large and varied industrial data base. A deliberate attempt was made to include repetitive jobs representative of a broad range of industries and to include a broad range of occupationally-related LBD risks so that the data and LBD risk model would be as generalizable as possible. This is one of few studies that has been able to quantify biomechanical factors *in vivo* during industrial work. This has provided a data base that will be useful for research purposes as well as for ergonomic application purposes. There are several benefits from such a study.

First, we are now able to identify and describe the trunk motions that workers are exposed to during MMH tasks in industry. These descriptions have indicated that there are considerably large three-dimensional trunk motions occurring in most industrial

Table 6. Multiple logistic regression model between the low and medium risk groups, and between the low and high risk groups.

Variables	Low vs. medium model: Coefficients	Low vs. medium model: Standard Error	Low vs. high model: Coefficients	Low vs. high model: Standard Error
Constant	− 0·905	0·59	− 3·02	0·75
Lifetrate	0·0023	0·0009	0·0032	0·0008
Average twisting velocity	0·009	0·40	0·011	0·052
Maximum moment	0·022	0·007	0·034	0·007
Maximum sagittal flexion	0·030	0·014	0·025	0·012
Maximum lateral velocity	0·012	0·014	0·015	0·017
Estimated odds ratio*	6·3		10·6	
Confidence interval	(2·9–14·0)		(4·8–23·1)	

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 for the model was computed with weighted means.

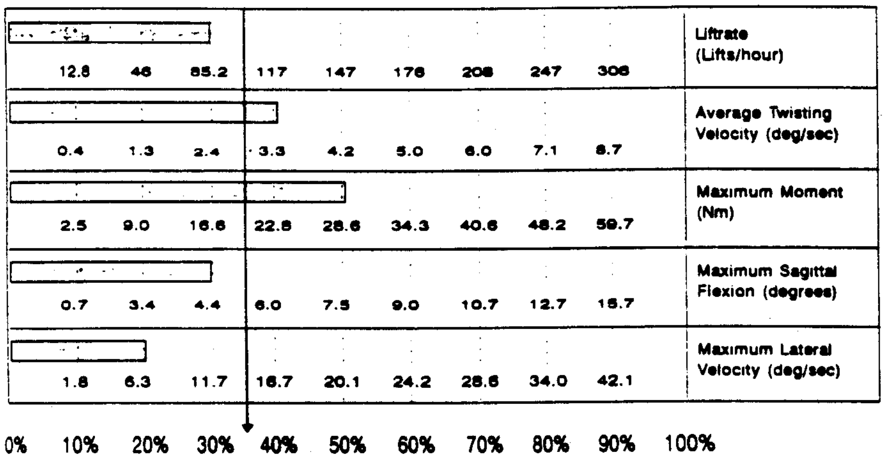

Figure 5. Probabilities of occupationally-related LBD (high risk group membership) shown as a function of the combination of five key risk factors defined by the multiple logistic regression model. Sagittal angle does not include resting lordotic angle.

tasks. This study has shown that the average lateral range of motion observed in industry was 16° (standard deviation: 7·6°) and the average transverse plane total range of motion was 4·4° (standard deviation: 2·4°). Significant dynamic trunk motions are also characteristic of industrial MMH tasks. The sagittal plane velocity measure achieved peak values that easily exceed 40°/s and could reach 200°/s. We have also found that maximum trunk acceleration could exceed $1000°/s^2$ in some planes of the body. These findings indicate that assumptions, such as those in current lifting guidelines (NIOSH 1981), of sagittally symmetric, slow, smooth lifting are not consistent with the types of motions that are experienced by the workers in the workplace.

Next, we have been able to determine which key workplace and trunk motion factors, and the magnitude of these factors, are indicative of both medium and high occupationally-related LBD risk. 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 factors (moment, lift rate, lateral velocity, sagittal trunk angle, and twisting velocity) used in the multiple logistic regression risk model, we are able to determine how a particular job relates to occupational LBD risk. 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 would result in a greater probability of LBD. This model also permits one to determine the effects of changing the specific values of the risk factors. This model has excellent predictive power and could identify over a ten-fold increase in odds of occupationally-related LBD. The model has immediate application potential for the ergonomic design and redesign of workplaces involving MMH.

This study has also demonstrated that the best discriminators of risk in the workplace are generally achieved by studying the maximum or peak measures of trunk motion and workplace factors. Similar conclusions were drawn by Herrin *et al.* (1986). Biomechanically extreme job elements are often not considered in current ergonomic evaluations. The notion that the maximum values of the workplace and trunk motion factors impact risk also has implications for the assessment of cumulative trauma disorders. Perhaps the variance in load demands on a biomechanical structure is a confounding factor in current attempts to understanding how the accumulation of stressors afects the tolerance of the structure.

Penultimately, these data can also be used to help to understand the conditions under which various biomechanical mechanisms operate during MMH. Since this data base is the only quantitative *in vivo* industrial data base 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 necessary 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 *et al.* (1990) 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 (Adams and Dolan 1991) 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. The present study provides such precise *in vivo* information about trunk movement characteristics that can be used for spine-related viscoelastic research purposes.

Finally, this information could be used to further trunk biomechanical modelling efforts. Biomechanical models that are sensitive to three-dimensional positions of the trunk (Chaffin and Muzaffer 1991, Marras and Sommerich 1991a, McGill and Norman 1986, Schultz and Andersson 1981) as well as those that are sensitive to dynamic trunk motions (Frievalds *et al.* 1984, Lindbeck and Arborelius 1991, Marras and Sommerich 1991a, McGill and Norman 1986, Reilly and Marras 1988) could use this 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 (Andersson *et al.* 1976a, 1974, 1976b, 1977, Lavender *et al.* 1991, Marras *et al.* 1985, 1984, Marras and Mirka 1990, 1992, Marras *et al.* 1986, Marras and Wongsam 1986, McGill and Norman 1985, Ortengren *et al.* 1981, Schultz *et al.* 1982, Serousi and Pope 1987) could use this information to define test conditions, thereby providing valuable insight as to how the musculoskeletal system responds to realistic industrial lifting conditions.

4.1. *Biomechanical implications*

This study has enabled us to determine, *in vivo* and in industrial environments, the magnitude 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 can be related to findings in the biomechanical and epidemiological literature.

Our study accentuates the fact that it is important to consider the three-dimensional actions and loadings of the spine during work. This study has shown that it is difficult to evaluate job risk when workplace factors are evaluated in two-dimensional, static positions alone. Previous industrial studies that have measured trunk position in the sagittal plane only have failed to show a relationship between trunk loading and back complaints (Magnusson *et al.* 1990). There is also evidence to suggest that disc damage does not occur unless load asymmetry is present. Shirazi-Adl *et al.* (1984), using finite element modelling, found that the annulus was not vulnerable to rupture under pure compressive loading. Thus, these studies as well as others (Andersson 1981, 1991, Magora 1973, Pope 1989, Shirazi-Adl 1991) 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 a significant amount of biomechanical evidence that supports the notion that the key risk factors identified in this study are related to risk. This evidence can be found in the biomechanical literature as well as through biomechanical modelling efforts.

4.1.1. *Motion:* This analysis has shown that motion, in particular velocity, is important in defining risk of occupational LBD. Table 5 indicates that the trunk velocity characteristics within each of the cardinal planes are often more predictive of LBD than position, range of motion, or acceleration. This was also identified through multiple logistic regression modelling. Models that employed trunk motion characteristics other than velocity were less able to discriminate LBD risk levels. Thus, the dynamic nature of the loading is a major factor in estimating risk. Several epidemiologic studies also indicate that motion is an important risk factor (Bigos *et al.* 1986, Magora 1973).

Biomechanically, increased motion may increase the risk of LBD for several reasons. First, the literature provides several forms of evidence that the viscoelastic properties of the osteoligamentous lumbar spine increase risk during dynamic motion but not under static conditions. Adams and Hutton (1986) found that when the spine was fully flexed, the osteoligamentous spine is 10° short of the elastic limit. This indicates that there is a built-in safety margin associated with postures and suggests that there is little chance of lumbar spine damage due solely to the assumption of extreme bending postures. However, these authors also point out that this margin of safety might be reduced or eliminated during rapid movements. This is due to the fact that the ligaments are visocoelastic and strongly resist fast deformation. Therefore, when faster rates of motion are included, 'sprains' occur at smaller flexion angles than during slower motions. Adams and Dolan (1991) as well as Hukins *et al.* (1990) have also demonstrated how motion influences ligamentous force.

Second, increased trunk motion during lifting could accentuate spine loading due to the behaviour of the musculoskeletal system. Marras and Mirka (1992) have investigated the response of the trunk musculature under isokinetic conditions that attempted to match motion conditions observed in the current study. They have shown that as trunk velocity increases, trunk muscle coactivation also increases. This would tend to magnify the loading on the spine since the muscles work against one another. Trunk motion models of the spine (Marras and Sommerich 1991a, 1991b) have also shown that as the trunk velocity increases during asymmetric lifting, significant increases in lateral shear forces occur on the spine.

It is interesting to note that acceleration was not chosen as the best indicator of dynamic trunk motion risk. Additional multiple logistic regression models were tested using lateral and twisting acceleration instead of velocity. These models did not produce odds ratios that were as large as the model containing velocity in the lateral and twisting directions. The mass of the trunk is large and rapidly accelerating motions are difficult to generate without further increasing muscle coactivation (Marras and Mirka 1990). Attempts to increase acceleration result in increased guarding, which stiffen the trunk resulting in increases in velocity, but do not permit the large peak accelerations seen in joints where little coactivation occurs (Schoenmarklin 1991). Thus, the trunk is less ballistic making acceleration a less significant characteristic indicator of motion compared to velocity. Lindbeck and Arborelius (1991) found that complete dynamic analyses of lifting motions (which included acceleration) add little to the evaluation of trunk loading once ground reaction forces were measured. Thus, since the trunk is a relatively slow moving structure, velocity may indeed be the most sensitive indicator of movement dynamics. This also indicates that biomechanical models that use isokinetic data may provide reasonable approximations of trunk loading during lifting.

4.1.2. *Lateral trunk velocity:* Preliminary multiple logistic regression models had suggested that lateral trunk velocity along with load moment were the two most powerful predictors in the logistic regession model. Rapid maximum lateral velocities indicate high risk conditions, whereas slow velocities are safe. The construction of the vertebrae with its neural arch adds considerable resistance to forward shear; however, lateral shear strength, which relies more on disc strength, is probably less than 900 N (Farfan 1988). The literature is rich with studies indicating that disc strain increases greatly as does risk of injury with lateral loading or combinations of plane loading (Broberg 1983, Lin *et al.* 1978, Schultz *et al.* 1979, Shirazi-Adl 1989, 1991, Shirazi-Adl *et al.* 1986, Shirazi-Adl and Drouin 1987, Shirazi-Adl *et al.* 1984). Trunk torque generation is also reduced in the lateral plane (McGill 1991a, 1991b, Parnianpour *et al.* 1991, 1988), which may increase the risk of overexertion.

4.1.3. *Twisting trunk velocity:* A limited range of twisting velocities appear to act synergistically with lateral velocity to define LBD risk. Twisting velocities, in our model, were fairly slow averaging 4·2°/s. Pearcy and Tibrewal (1984) observed that axial rotation and lateral bending generally accompanied each other in the same direction at L5/S1. Thus, twisting velocity may act in conjunction with lateral trunk velocity to increase risk. Duncan and Ahmed (1991) have shown that with an intact facet joint, axial rotation does not impose unusual stress on the structure. However, when rotation is combined with bending (a high risk combination according to our risk model) the axial range of motion is reduced and loading patterns change significantly (Gunzburg *et al.* 1991). This is most likely due to variance in the load path through the superior and inferior articular processes during complex loading (Lin *et al.* 1978, Parsad and King 1974). Shirazi-Adl *et al.* (1986) have shown that when lateral bending and twisting occurred simultaneously, the disc fibre stain increased markedly. Shirazi-Adl (1989) has also shown that when axial torque is combined with compression the disc fibres located at the posterolateral and posterior locations of the spine become more vulnerable when combined with bending moments. In a more recent study Shirazi-Adl (1991) reported that when lateral bending and twisting occur during lifting, facet compressive and shear contact loads significantly increase. This would increase the risk of facet injury and degeneration. These loadings would be exacerbated according to our risk model with even slow twisting velocities.

The effects of trunk torsional velocity have also been studied under motion (isokinetic) conditions. McGill (1991a, 1991b) showed that the latissimus dorsi and external oblique muscles became predominant during the generation of torsional torque, thereby increasing shear loading of the spine.

4.1.4. *Sagittal flexion angle:* The only position related factor in the risk model was the maximum sagittal angle observed during a lift cycle. The model suggests that when the maximum sagittal angle of the lumbar spine is low and maintained at an angle close to an upright posture during a lift the risk of LBD is significantly decreased. In this posture the facet joints carry a portion of the spine loads (Shirazi-Adl and Drouin 1987). However, as the sagittal flexion angle increases, risk increases. The lumbar spine flattens in these flexed positions and the intervertebral disc must bear most of the load. Berkson *et al.* (1979) found that when support from the posterior elements is eliminated, anterior shear can increase by as much as 60%. This makes the disc more susceptible to strain from the lateral shear and torsional forces. Edwards *et al.* (1987) also showed that the functional spinal units are much stiffer in flexion compared to extension, especially under high load conditions. These studies emphasize the multivariate nature of spine loading that can only be addressed by multivariate models.

4.1.5. *Moment:* The moment defines the nature of the external load applied to the muscloskeltal and oesteoligamentous disc system. Both the individual logistic regressions (table 5) as well as the multivariate risk model indicate that peak load moment plays a major role in defining LBD risk. Our risk model identified high risk moments at 60 Nm. High risk loads of this magnitude agree with the magnitude of high risk loads identified in the literature. Numerous sources (Chaffin and Park 1973, Clemmer *et al.* 1991a, 1991b, Herrin *et al.* 1986, Magora 1970a, 1970b, Punnett *et al.*

function of a weighted sum of the risk factors in the model, the model implies that risk factors can be 'traded' to achieve desired low probabilities of LBD. For example, in industrial settings, it may not be possible to match a desired low probability of injury (such as 10%) by lowering the load weight alone. If a given load weight is unavoidable, a reduction of the other risk factors in the model (such as lift rate, maximum sagittal angle, lateral velocity, and twisting velocity) may yield the desired estimated probability of LBD without changing the moment. The concept of trade-off between the nature of loadings on the spine was discussed by Broberg (1983), Adams and Dolan (1991), and Shirazi-Adl (1989) who demonstrated that linear combinations of changes in bending, shear, or torsion would have the same effect on the disc as increasing the axial load by a given amount.

4.2. *Other considerations*

One may question whether the position of the extremities and pelvis might be a potential confounding factor in this study. Lower extremity position (Anderson *et al.* 1986, Schipplein *et al.* 1991) and upper extremity position (Gagnon and Smyth 1991) may influence the LMM determined sagittal angle component of the risk model. Upper and lower extremity extreme positions would particularly affect the sagittal angle. In our study few squat lifts, which would influence knee, arm and pelvic angles, were observed. Nevertheless, documentation of knee position and upper extremity position along with trunk flexion angle may further improve predictability of occupationally-related LBD in future investigations.

This effort has reviewed MMH activities in the industrial environment. We have assumed that there is a linear relationship between low risk and high risk MMH jobs. The tasks contributing to this data base can be compared with those occupations studied by Videman *et al.* (1990). In that study researchers found that risk was least with moderate activity and increased with sedentary or heavy activity (U-shaped function). Our data base would correlate with the moderate and high loading specimens of Videman *et al.* (1990). We did not study sedentary jobs. Thus, our linear or at least monotonic relationship assumed in the multiple logistic regression risk model would be valid since we are essentially studying half of the U-shaped function described by Videman *et al.* (1990).

Further studies are needed in three areas. First, there is a need to explore the biomechanical significance of the risk benchmarks. Some studies (Marras and Mirka 1992, Marras and Sommerich 1991a, 1991b) have investigated the trunk musculature response and subsequent spine loading occurring during motion. More dynamic analyses that target specific combinations of risk factors are needed. Second, one needs to investigate closely the effects of spine complex loading upon the determination of risk factors. This could facilitate MMH-related biomechanical evaluations at the segmental level. Third, a longitudinal study is needed to validate the findings in this study. This cross-sectional study was performed with a relatively large industrial data base and helped to identify levels of the risk factors that incease risk. A longitudinal study is needed to confirm these findings and is currently underway in our laboratory.

5. Conclusions

Based upon this study the following conclusions can be drawn.

1. Significantly large trunk range of motion, velocity, and accelerations in the

1987, Schipplein *et al.* 1991, Svensson and Andersson 1989) have implicated large weights or distances from the spine as risk factors that increase the compressive load on the spine during work. Andersson *et al.* (1976b) demonstrated how disc pressure increased nonlinearly as a function of both increased load in the hands as well as increased trunk flexion angle. This finding indicated that the moment about the spine determines spine compression.

There is also a tie between the moment and the sagittal trunk angle factor. Spine shear force (Potvin *et al.* 1991) and disc fibre tensile strain (Shirazi-Adl 1989) increase significantly when compression and bending occur together. Adams and Dolan (1991) developed a technique to derive bending moment at L5/S1 from *in vivo* trunk flexion angle. Using their technique we estimated that the static bending moment limit would correspond approximately to our 100th percentile sagittal flexion value. Of coure, this limit would vary according to individual flexibility and the influence of other risk factors such as motion and external moment. However, this indicates that our risk model accounts for reasonable bending moment risk values.

4.1.6. *Liftrate:* The final variable in the model was liftrate. This study has shown that the risk of injury increases when more than 120 lifts per hour were performed. This agrees with the cumulative trauma threshold value of Putz-Anderson (1988). The literature also suggests that frequency of lifting is related to risk of LBD. Through epidemiologic studies, Magora (1973) and Kelsey *et al.* (1984) have shown frequency of loading to be an important occupational risk factor. Snook (1978) has reported that 94% of industrial lifts occur at rates lower than 4.3 lifts per minute (258/hr). This rate approximates the 82nd percentile risk seen in our model. Thus, our levels of frequency exposure are similar to those found by other researchers.

The impact of cumulative trauma upon the musculoskeletal system has become apparent in recent years. Repetitive loading is now considered one of the major components of occupational illness (Silverstein *et al.* 1986, US Department of Labor 1989). Brinckmann *et al.* (1988) have shown a close association between load magnitude, load frequency and spine failure rate. However, there appears to be a complicated relationship between loading frequency and injury risk. Videman *et al.* (1990) showed that there is a U-shaped association between occupational loading and LBD risk, indicating that those who experienced excessive loading or had sedentary jobs were at the greatest risk of injury. Thus, a moderate frequency of loading may be beneficial.

4.1.7. *Combined effects:* It should be re-emphasized that even though the risk factors have been discussed independently, the multiple logistic regression model identifies risk as a function of a *combination* of factors. Generally, this study has established that the risk of LBD is increased as a function of liftrate, lateral and twisting motions, trunk flexion angle, and external moment. Several studies (Farfan 1988, Gunzburg *et al.* 1991, McGill 1991a, 1991b, Pearcy and Tibrewal 1984, Shirazi-Adl 1991, Strachan 1979, Troup and Edwards 1985) have acknowledged the increased risk associated with combinations of these risk factors. However, the value of this study is that we have been able to study the combination of these risk factors in industrial environments and specify a numerical combination of risk factors that would increase the risk of injury. Realistically, this means that we are able to specify limits for industrial tasks that should substantially lower the risk of occupationally-related LBD.

Since probability of LBD, in a multiple logistic regression mode, is modelled as a

cardinal planes are associated with industrial MMH. These motions have been quantitatively described.
2. Trunk motion 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 LBDs have been associated with a combination of five measures representing both workplace and trunk motion factors. As trunk velocity becomes more rapid the risk of LBD increases.
4. We have been able to identify the levels of workplace and trunk motion factors that, in combination, define occupationally-related LBD risk.
5. This information could be used to redesign workplaces as well as to understand the nature of occupationally-related injury. Futhermore, this data can also be used to define biomechanical reasearch efforts so that occupational conditions are better simulated.

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