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A comparison of peak vs cumulative physical work exposure risk factors for the reporting of low back pain in the automotive industry

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Abstract

Objective. To determine the relative importance of modelled peak spine loads, hand loads, trunk kinematics and cumulative spine loads as predictors of reported low back pain (LBP).

Background. The authors have recently shown that both biomechemical and psychosocial variables are important in the reporting of LBP. In previous studies, peak spinal load risk factors have been identified and while there is in vitro evidence for adverse effects of excessive cumulative load on tissue, there is little epidemiological evidence.

Methods. Physical exposures to peak and cumulative lumbar spine moment, compression and shear forces, trunk kinematics, and forces on hands were analyzed on 130 randomly selected controls and 104 cases. Univariable and multivariable odds ratios of the risk of reporting were calculated from a backwards logistic regression analysis. Interrelationships among variables were examined by factor analysis.

Results. Cases showed significantly higher loading on all biomechanical variables. Four independent risk factors were identified: integrated lumbar moment (over a shift), 'usual' hand force, peak shear force at the level of L_4/L_5 and peak trunk velocity. Substituting lumbar compression or moment for shear did not appreciably alter odds ratios because of high correlations among these variables.

Conclusions. Cumulative biomechanical variables are important risk factors in the reporting of LBP. Spinal tissue loading estimates from a biomechanical model provide information not included in the trunk kinematics and hand force inputs to the model alone. Workers in the top 25% of loading exposure on all risk factors are at about six times the risk of reporting LBP when compared with those in the bottom 25%.

Relevance

Primary prevention, treatment, and return to work efforts for individuals reporting LBP all require understanding of risk factors. The results suggest that cumulative loading of the low back is important etiologically and highlight the need for better information on the response of spinal tissues to cumulative loading.

Keywords: Low back pain; epidemiology; auto assembly; spinal load; trunk kinematics; biomechanical spine model; shear; compression

1. Introduction

Physical loading on the low back at work, in particular high peak forces and adverse trunk postures and movements, have been presented as contributors to the reporting of low back pain (LBP) in industry [1–3]. Cumulative physical loading of spinal tissues is often also assumed to be a risk factor related to occupational LBP, and some in vitro biomechanical evidence regarding adverse effects of excessive cumulative loading on tissues is available [4,5], but epidemiological evidence is meagre. Indeed, the only study found by the authors that presented any data to relate the reporting of LBP to accumulated load estimates was by Kumar [6] which suggested that estimates of compression and shear accumulated historically over the entire work experience were significantly higher in

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male institutional aides with back pain than in those without it. It must be noted, however, that measures of physical demands of jobs have not been unaminously acknowledged as risk factors for the reporting of LBP [7–9].

The data presented in this paper focus on the biomechanical part of a case-control epidemiological study in which possible psychosocial, biomechanical and demographic risk factors that might be related to the reporting of LBP by assembly and assembly support workers were measured in detail in a large automobile company. When all three types of potential risk factors were studied simultaneously, the data showed that both biomechanical and psychosocial variables are important and result in statistically significant, independent risk contributions according to a multivariable statistic analysis model that clearly separated those who reported (cases) and those who did not report LBP (controls) at work. Specifically, the following variables emerged as independent risk factors for LBP: peak shear force on the lumbar spine, cumulative compression on the lumbar spine integrated over the duration of a shift, usual force (as opposed to peak force) on the hands, worker perceptions of high physical demand, poor workplace social environment, low job control but, high (not low) co-worker support, high (not low) job satisfaction and better education relative to those who performed similar jobs. The results of the combined analysis suggest that if workers were high on all of those risk factors the odds for reporting LBP would be approximately 15:1. Although there were no significant differences between cases and controls in personal variables such as body mass index, age or smoking, the final model included terms to adjust for these demographic variables as well as a term for prior LBP history since, as expected, cases had a stronger history than controls [10,11].

A complete analysis of the combined biomechanical, psychosocial and demographic variables will be reported in another paper. However, because the results of the combined data suggest that there is an independent role for the biomechanical demands of work in the onset of LBP, and because the study collected, for the first time to the knowledge of the authors, extensive data on all three types of variables on the same workers, it is, therefore, important to thoroughly analyze the ability of biomechanical variables alone to distinguish between cases and controls, in the absence of the psychosocial risk factors. This focused analysis of biomechanical data is the substance of this paper.

Several types of biomechanical exposure variables related to low back troubles have been reported. They include external loads in the hands [12–14], kinematic variables such as torso angle [2,3] and velocity [2], and kinetic variables such as lumbar moments of force [2] and estimates of forces on lumbar spine structures from biomechanical spine models [1]. To assess job risk, biomechanists sometimes compare peak spinal loads, such as lumbar compression estimated from biomechanical models, to ultimate compressive strength of cadavar lumbar motion units [15].

For people who go off work because of pain, one might expect that biomechanical variables that approximate forces on tissues would be better exposure measures than 'surrogates' of tissue loading, such as external forces on the hands or trunk kinematic variables. The argument is that pain is a result of irritation or damage to tissue and the closer one can come to measuring exposure at the tissue level the stronger one might expect the relationships with reported pain to be. Spinal compression and shear and the extensor moment of force in the lumbar spine, produced primarily by muscle and ligament, are examples of tissue loading variables. Of course, if spine model outputs are merely combinations of hand force and kinematic inputs and reveal no more information about tissue loading than the individual inputs themselves, appropriate statistical treatment should eliminate one or more members of highly correlated combinations of these variables. If variables from the outputs of a biomechanical spine model are, indeed, eliminated from multivariable statistical models of risk factors, the continued use of spine models to assess occupational LBP risk could be questioned because of lack of epidemiological evidence to offset controversy surrounding assumptions in different models and problems in their direct validation.

1.1. *Purpose of the paper*

The purpose of this paper is to identify, by means of data from a case-control epidemiological study, biomechanical risk factors related to the reporting of LBP in the auto assembly industry. In particular, assessments were made to determine whether 'cumulative' physical loads on the lumbar spine are associated with risk of reporting LBP and whether estimates of lumbar spine tissue loading variables from a biomechanical spine model better separates cases from controls than the more straightforward measures of forces on the hands and/or trunk kinematic variables that are inputs to spine models.

1.2. *Hypotheses*

1. There are biomechanical variables, of varying strength of association, that distinguish people who

report LBP (cases) from those who do not report pain (controls).

2. There are variables that characterize ‘cumulative exposure’ to load that provide information that is different from ‘peak load’ variables in the prediction of those workers who report LBP and those who do not.
3. Estimates of spinal compression, shear and the torso extension moment of force at the level of L4/L5, regardless of whether they are peak or cumulative loading estimates, will be better able to distinguish cases from controls than ‘surrogates’ of these forces on tissues such as kinematic or external loading variables.

2. Methods

A case-control study was conducted to identify the main work-related biomechanical and psychosocial risk factors for reported LBP in a large automotive assembly facility. The study base consisted of over 10000 hourly paid workers, including skilled trades, maintenance, and assembly line workers. Cases were defined as any full-time, hourly-paid worker who reported LBP to one of the nursing stations on site. Cases were not required to have lost time from work or to have submitted a disability claim, but they were eligible only if they had not reported LBP within 90 days of their current report of LBP. Controls were selected randomly from computerized employee rosters and rectruited simultaneously with the reporting of LBP by cases to achieve incidence density sampling, where odds ratios in case-control studies accurately estimate the relative risks obtained in prospective cohort designs.

Each participant received a home visit for a detailed, interviewer-administered questionnaire on psychosocial, demographic and clinical factors. After the baseline evaluation of these factors was complete, workers’ exposure to physical loading in the workplace was assessed using a comprehensive set of biomechanical methods while the participants were working on their regular jobs [16]. The data presented in this paper were obtained from a video-based posture analysis system [17] and a 2D, quasi-dynamic biomechanical model of L_4/L_5 spinal loading forces from video-captured coordinate data [18]. In all, extensive biomechanical measures were made over a two-year period on more than 250 workers for observation durations ranging from two to eight hours during a normal work shift. Typically, workers were observed for approximately half a shift, about four hours.

In some situations, such as when an injured worker did not return to work, or the worker changed jobs following recovery from injury, it was not possible to collect workplace physical loading data on the case participant. In these instances a trained observer identified the case’s job and attempted to find a ‘job-matched control’, defined as someone performing the same work duties at the same rate as the missing case. Data from these job-matched controls were substituted into the analyses as a proxy to the missing case data, a procedure that has been used previously [3]. Twenty out of 104 cases were represented by proxies, a substitution that was intended to increase statistical power, although it also carried the risk of possibly reducing differences in measured risk factors between cases and controls, should any exist.

3. Spinal tissue load estimation

Spinal loading was monitored on the work site by a trained observer while the worker was performing regular work duties. The observer would identify all occurrences of ‘substantial’ spinal load by estimating instants of high spinal moments resulting from forward inclined trunk postures and/or high forces on the hands. The observer would then record the posture, size and directions of forces on the hands, duration of the effort, and the number of repetitions of that instant of increased loading. Forces acting on the hands were usually measured using a force transducer. In cases where the transducer could not be inserted between the worker and the work, the worker was asked to push or pull the transducer against resistance to the side of the workstation until he/she produced their estimate of the same effort. The directions of forces on the hands were estimated and recorded by one of the observers trained in the use of the biomechanical spine model. Each of these tasks was then located on the video recording of the participant and the frame which best characterized the peak spine loading instant of the task was captured for computer analysis. In many cases several frames around the suspected peak instant were analyzed for a task and these frames, which provided a sagittal view of the worker, were then manually digitized to provide joint coordinate data and combined with the hand force information recorded in the field to provide input for a biomechanical spine model. The highest spinal load estimate resulting from all of the task peak instants identified for one job was taken to be the peak spine load for that worker.

Jobs comprised several tasks. The cumulative load exposure due to each task identified in a job was estimated by multiplying each of the task peak instants by the number of times that task was performed during the shift and by the duration of the exposure for each task. The integrated load experienced by the worker over the course of a complete shift was then calculated by summing these separate task integrals. Spinal loading during the time spent between work tasks was included in this estimate by multiplying the spinal load estimated in an upright standing posture by the total time spent in this waiting phase. Workers would stand and talk or sometimes support the weight of their head, arms and trunk by leaning on a bench while they read a few paragraphs in a newspaper or book during waiting periods. The cumulative loading estimates assume that the supported trunk postures resulted in spinal loading that was no greater than that observed during upright standing in all of these waiting periods.

The biomechanical model of the lumbar spine used in this study merits description because outputs from the model were extensively used. It is a quasi-dynamic, two-dimensional, 15-member, linked-segment model. Asymmetric body postures can be input. Magnitudes and directions of dynamic or static forces acting on each hand separately were entered into the model. When dynamic forces acting on the hands were input, their effects were seen in the model output; body segment inertial forces were not included. Thus, the model (watbak) is partially dynamic and for this reason the term quasi-dynamic was used to describe it [18]. This quasi-dynamic approach has been shown to produce higher estimates of spinal loading than those from fully dynamic linked-segment models [18]. The time cost of reducing data from more than 230 workers and more than 1000 tasks was dramatically lower than it would have been if a fully dynamic model had been used. The quasi-dynamic model partially incorporates the well-known and important effects of dynamic loading on the spine [18, 19]. The effects of the accelerations of loads on the hands are included but effects of body segment accelerations are not. Anthropometrics for segment masses and locations of mass centres for men and women were taken from Plagenhoef [20] and Zatsiorsky and Seluyanov [21]. The participant's body weight and gender were specified. Postural input was obtained from digitized *x,y*-coordinates of body jonts or, if digitized video data were unavailable, via on-screen manipulation of a moveable mannequin.

The model calculated forces and moments at each joint starting at the wrist of each arm and proceeding to the elbow, shoulder, seventh cervical vertebra and down to the L_4/L_5 joint. Compression and shear forces at the L_4/L_5 level were estimated from knowledge of the moment of force and reaction forces at this motion unit. A 6-cm moment arm length was used to represent the geometry of a single equivalent torso extensor 'muscle' for the estimation of the compression component. This moment arm length was incorporated as a result of findings from work with a fully dynamic, much more anatomically detailed, EMG-assisted model [22], [23]. Anatomical dissection of lumbar musculature shows that there is a posterior pulling component of a substantial number of fascicles that tend to reduce anterior shear of the upper body when lumbar muscles are active [22–24]. These muscles are active if the lordotic curvature is maintained. If it is lost, ligaments are activated to support the load moment but they increase anterior shear [22–24]. The model incorporates these effects on shear forces acting on the lumbar spine and the output is called 'joint shear', as distinct from 'reaction shear'. In the data presented, only reaction shear is analyzed and both anterior reaction shear of L_4 on L_5 (i.e. head, arms and trunk tending to slide forward on L_5) and posterior reaction shear were calculated and entered into the regression model. Anterior shear was more common because this direction of shear is observed with the torso in a forward inclined posture, with or without load on the hands, and during pulling activities in an upright posture. Shear in the lateral transverse plane or shear as a result of spinal torsion was not calculated and would have elevated the shear force estimates reported in tasks with substantial lateral bend or torsional moments. All trunk kinematic and spine loading data entered into the model were in the sagittal plane.

4. Posture analysis system

Working postures, as distinct from spinal loading estimates described in the previous paragraphs, were analyzed using a computer-assisted video analysis system whose reliability and accuracy are documented elsewhere in the literature [17]. The system allowed an operator to use joystick input to track the joint postures seen in a section of digitized video over the course of the video clip. The computer handled all data synchronization and correction functions and provided visual feedback to the operator through an animated mannequin figure.

During the field data collection process the trained observer identified the separate components of the job to be analyzed. A representative trial of each of the components was then located on the video recording, digitized, and analyzed for trunk flexion/extension, torsion and lateral bending movements. Torsion was recorded as 'yes/no' if estimated to be greater than 20°. For short, highly repetitive work components, several cycles of repetitions were digitized and analyzed as a group while longer sections of work had representative portions digitized. Trunk flexion and lateral bend were defined as the angle of inclination of the L_4–C_7 line with respect to the vertical. The trunk angle over the course of each section of video was sampled at 30 Hz and the raw data were low pass filtered at 3 Hz.

The amplitude probability distribution function (APDF) of the trunk flexion/extension trace for each work component was combined into a time-weighted average to represent the APDF of trunk posture for an entire shift. Peak posture variables used for this study included the peak trunk flexion and the peak trunk velocity. The 99th percentile of the APDF was used to represent the peak values instead of the highest single value because the highest single value in the sample could have been caused by operator overshoot during the data processing stage. Cumulative postural exposure over the full shift was represented by the average number of trunk movements and by the average number of degrees moved per minute. A trunk movement was defined as any unidirectional movement with an amplitude of at least 20°. The APDF also permitted calculation of the percentage of the job cycle duration for which any particular trunk angle of interest was adopted by the worker.

In summary, many trunk kinematic and spinal tissue loading variables were recorded or calculated. They included peak and average trunk flexion angles, number of trunk movements (flexions or extensions) per minute, presence or absence of trunk twist or lateral bend, percentage of cycle time spent at various angles, peak and average trunk flexion and extension velocity, peak and accumulated L_4/L_5 moment, compression and shear. The 'peak load' variables that were statistically analyzed and presented in this paper are: lumbar spine compression, shear, and moment at the L_4/L_5 level, trunk flexion angle, trunk flexion velocity, and force on the hands experienced during a shift. These peak load variables were matched, respectively, with the following 'cumulative loading' variables: integrated spine compression, shear, and moment at L_4/L_5 over a shift, the time averaged number of degrees of flexion/extension excursion per minute, the number of flexion/extension moves per minute and the 'usual' force on the hand.

5. Statistical analysis

The interrelationships between variables were examined by constructing a Pearson correlation matrix. An exploratory factor analysis with a varimax rotation was then performed on the data to further examine intercorrelations of variables and to see which variables could be grouped to better explain the total exposure variance. Mean levels of all biomechanical variables were also examined independently to test for differences between cases and controls using a Student's *t*-test. Univariable odds ratios (ORs) were calculated for all variables using logistic regression procedures (SAS).

The complex relationships between the study variables and risk of reporting LBP were examined using multiple logistic regression with backwards elimination of variables that did not significantly contribute to the statistical model. To avoid over-restricting the choice of variables included in the preliminary models, we first identified variables that, univariabily, met a significance threshold of $P = 0.10$. These variables were candidates in the multivariable analysis although only those risk factors in the regression significant at $P = 0.05$ were retained in the final model. The multivariable technique allows for the identification of the study variables with the greatest independent contribution to outcome by simultaneously accounting for all variables that are entered into the analysis. The extent of the independent relationships of the study variables with LBP was assessed by calculating the odds ratio (OR), the estimator of risk for case-control studies. A value of 1.0 for the OR indicates an absence of risk. The statistical precision of the OR estimates was determined by calculating the corresponding 95% confidence intervals (95% CI). These intervals provide the most likely upper and lower bounds for the OR estimate. OR estimates of variables not statistically significant at the $P = 0.05$ levels have a 95% CI that includes 1.0 [25].

Since all of the biomechanical variables were on continuous scales, the size of the OR depends on the size of the unit exposure difference used to calculate it. While the default difference in exposure is a single unit of the variable in question (e.g. 1 Newton compression) such a unit difference is not relevant for exposure variables which have very large ranges (e.g. thousands of Newtons). Therefore, to better represent the risk associated with the study variables, two different ranges of exposure difference were chosen to report the odds ratio. A conservative estimate of risk was calculated by using the inter-quartile spread (IQS) as the unit difference. In this study, the IQS was taken to be the difference between the 25th and 75th percentile of exposure levels seen in the randomly sampled control group of plant workers. An estimate of the maximum risk was derived using the full range of exposure (100% range) seen in the data from the jobs of the randomly selected control group. The maximum risk estimate indicates the risk difference between the single least exposed and the single most exposed worker for that variable, an analytic strategy used previously [3]. The OR calculated across the IQS will always be smaller than the OR calculated across the 100% range but may provide a more realistic target for job improvements. The use of these ranges to calculate the OR permits interpretation of the risk levels within the context of exposure ranges present in the plant.

In this data base, in which only complete data sets on all of the biomechanical variables of interest were analyzed, data on 104 cases (including 20 job-matched proxies) and 130 random controls are presented.

6. Results

The demographic data on cases and controls are presented in Table 1. There were no significant differences at $p < 0.05$ on any variable. Therefore, age, height, weight and work experience were not controlled in the logistic regression analyses presented in this paper because they did not distinguish cases from controls [10, 11].

Biomechanical data means, standard deviations, and the results from the *t*-tests are presented in Table 2. There were significant differences between cases and controls for all biomechanical variables presented in this paper; peak variables were all significant at $p < 0.001$ and cumulative variables were all significant at $p < 0.05$.

The matrix of Pearson correlation coefficients is presented in Table 3. Strong correlations were found within the peak spinal loading variables and within the cumulative loading variables but the correlations between the two types of variables were low. Peak hand force correlated strongly with usual hand force, while both hand force variables correlated only moderately with the peak spinal tissue load variables of compression, moment and shear. Peak velocity, average number of trunk movements, and the average number of degrees moved per minute were all strongly intercorrelated and all of these posture variables were moderately correlated to peak flexion level.

The results from the factor analysis, using four orthogonal factors, are presented in a factor loading matrix shown in Table 4. Together, four factors in the analysis accounted for 89% of the total variance and all variables had a final communality ranging from 0.70 to 0.97 indicating that most of the variance of each contributing variable was accounted for in a four-factor

Table 1
Demographic data on those who reported LBP (cases) and those who did not (controls)

	Cases		Control		Prob
	Mean	SD	Mean	SD	
Age (yr)	41.1	8.5	41.5	8.2	0.63
Height (cm)	177.2	7.1	176.2	7.0	0.23
Weight (kg)	83.6	14.2	83.4	13.3	0.87
Body mass index (BMI)	26.6	3.9	26.8	3.9	0.60
	Case (%)		Control (%)		χ^2 p-value
Gender (male)	92.0		92.7		0.80
Current smoker	45.3		41.9		0.55
Main wage earner in household	81.8		78.8		0.51
Lives with pre-school children	21.2		19.0		0.63
Married	76.5		84.8		0.06

Table 2
Comparisons of peak and cumulative load variables including mean, standard deviation (SD), and probability level for case versus control differences (Prob). Integrated load variables are calculated over a complete shift

Variable	Cases			Controls			t Value	Prob.
	n	Mean	SD	n	Mean	SD		
Peak compression (N)	104	3423	1421	130	2733	1073	4.10	0.0001
Peak moment (N m)	104	182	84.3	130	140	62.7	4.15	0.0001
Peak shear (N)	104	465	176	130	353	159	5.10	0.00001
Peak hand force (N)	104	222	201	129	134	123	3.87	0.0002
Peak flexion (deg)	104	51.2	22.4	130	39.3	23.3	3.94	0.0001
Peak trunk velocity (deg s^{-1})	104	41.5	15.14	130	34.1	17.2	3.42	0.0007
Integrated compression (MN s)	104	21.0	4.72	130	19.5	3.84	2.68	0.0079
Integrated moment (MN m s)	104	0.55	0.24	130	0.47	0.15	2.96	0.0036
Inegrated shear (MN s)	104	1.52	0.64	130	1.32	0.45	2.61	0.0097
Usual hand force (N)	104	86	67	129	56	52	3.85	0.0002
Average moves (min^{-1})	104	2.9	2.1	130	2.3	2.3	2.08	0.0384
Average flexion (deg min^{-1})	104	307.5	137	130	252.3	133.3	3.11	0.0021

(MN s = megaNewton seconds per shift; MN m s = megaNewton meter seconds per shift)

Table 3
Pearson correlation coefficients matrix for all variables

Variable	1	2	3	4	5	6	7	8	9	10	11	12
1. Peak compression	1.00											
2. Peak moment	**0.97‡**	1.00										
3. Peak shear	**0.83‡**	**0.89‡**	1.00									
4. Peak hand force	*0.66‡*	*0.63‡*	*0.58‡*	1.00								
5. Peak flexion	0.33‡	0.40‡	0.48‡	0.24‡	1.00							
6. Peak trunk velocity	0.16†	0.22‡	0.26‡	0.09	*0.68‡*	1.00						
7. Integrated compression	0.24‡	0.24‡	0.30‡	−0.03	0.14‡	0.06	1.00					
8. Integrated moment	0.15†	0.17‡	0.24‡	−0.04	0.30‡	0.21‡	**0.88‡**	1.00				
9. Integrated shear	0.12	0.15†	0.25‡	−0.05	0.39‡	0.27‡	**0.78‡**	**0.93‡**	1.00			
10. Usual hand force	*0.59‡*	*0.56‡*	*0.49‡*	**0.82‡**	0.09	−0.05	0.00	−0.01	−0.04	1.00		
11. Average moves	0.04	0.08	0.14†	0.04	*0.60‡*	**0.82‡**	0.04	0.21‡	0.28‡	−0.07	1.00	
12. Average flexion	0.12	0.15†	0.17†	0.07	*0.52‡*	**0.84‡**	0.07	0.22‡	0.26‡	−0.05	**0.78‡**	1.00

†Statistically significant correlation $p < 0.05$.
‡Statistically significant correlation $p < 0.01$.
Strong correlation $r < 0.70$.
Moderate correlation $r < 0.50$.

model. These results support data from the correlation matrix indicating strong interrelationships within the distinct sets of peak and cumulative spine loading variables, but not between these sets. Therefore, it appears that the cumulative loading variables are not simply the values of peak variables multiplied (or divided) linearly by time.

The univariable odds ratios were significant for all variables and are summarized in Table 5 for the IQS and in Fig. 1 for the 100% range from observations of the random control group exposure. The IQS odds ratios are statistically significant for all variables and indicate substantial risk. Peak shear force and peak torso flexion stand out with the ORs of reporting back pain, respectively, of 2.3 and 2.4 between workers with exposure differences equal to the inter-quartile spread. The OR estimates based on 100% of the range (the extremes of exposure), are much larger.

The final multivariable logistic regression model of the biomechanical measures, in the absence of any psychosocial variables, contained four risk factors. Table 6 shows the ORs of each variables for the IQS and 'full range' of their values. Since each OR is adjusted for the effects of the other three variables, these four variables constitute independent risk factors. Based on the underlying assumptions of the logistic regression model used, the combined OR is calculated by multiplying the individual risk factor ORs in the multivariable model. For workers exposed to levels of all four biomechanical variables equal to the IQS, a completely feasible possibility, the combined risk estimate is over 6.0. Two peaks and two cumulative variables emerged in the final model: peak lumbar shear force; peak torso flexion velocity; the integrated lumbar moment over the duration of the shift; and the time averaged 'usual hand force'. For the same

Table 4
Rotated factor loading matrix from principal components analysis using four factors. Each variable's largest loading factors are marked in bold. Factor loadings <0.1 are excluded

Variable name	Factor 1 Trunk kinematics	Factor 2 Peak spine load	Factor 3 Integrated spine load	Factor 4 Hand force
Peak compression (N)		**0.89**		0.34
Peak moment (N m)		**0.93**		0.28
Peak shear (N)	0.15	**0.89**	0.18	0.22
Peak hand force (N)		0.45		**0.83**
Peak flexion level (deg)	**0.71**	0.40	0.17	
Peak trunk velocity (deg s^{-1})	**0.94**	0.12		
Integrated compression (N s)		0.19	**0.92**	
Integrated moment (N m s)	0.15		**0.97**	
Integrated shear (N s)	0.23		**0.92**	
Usual hand force (N)		0.34		**0.90**
Average moves (min^{-1})	**0.92**			
Average flexion (deg min^{-1})	**0.90**			

Table 5
Univariable odds ratios (ORs), 95% confidence interval (CI), and model details from logistic regression analysis. Odds ratios were calculated for exposure differences equal to the random control inter-quartile spread (IQS) for both peak and cumulative loading variables. Odds ratios for which the 95% confidence interval does not span 1.0 are significant at $p < 0.05$

Variable	Chi-square	IQS difference	OR at IQS difference	95% CI
Peak compression (N)	15.24	1348	1.9	1.4–2.6
Peak moment (N m)	15.54	79.9	1.9	1.4–2.6
Peak shear (N)	20.79	203	2.3	1.6–3.4
Peak hand force (N)	13.63	167	1.8	1.3–2.5
Peak flexion (deg)	14.04	39	2.4	1.5–3.8
Peak trunk velocity (deg s^{-1})	10.76	22.6	1.9	1.3–2.7
Integrated compression (MN s)	7.01	4.62	1.5	1.1–2.0
Integrated moment (MN m s)	8.26	0.21	1.6	1.2–2.2
Integrated shear (MN s)	6.55	0.53	1.4	1.1–1.9
Usual hand force (N)	13.19	70	1.9	1.4–2.7
Average moves (min^{-1})	4.18	2.9	1.4	1.0–2.0
Average flexion (deg min^{-1})	8.93	176.6	1.7	1.2–2.5

(MN s = megaNewton seconds per shift; MN m s = megaNewton meter seconds per shift)

variables, but assigning the unit differences as the 100% range of the random control observations instead of the IQS, the combined relative risk for people working at the high end on all four variables is very large. It is, however, improbable that someone would be exposed to extreme levels on all four variables.

7. Discussion

Although several biomechanical (and psychosocial) variables clearly separated cases from controls and an array of specific, independent biomechanical variables surfaced as risk factors, there are a number of limita-

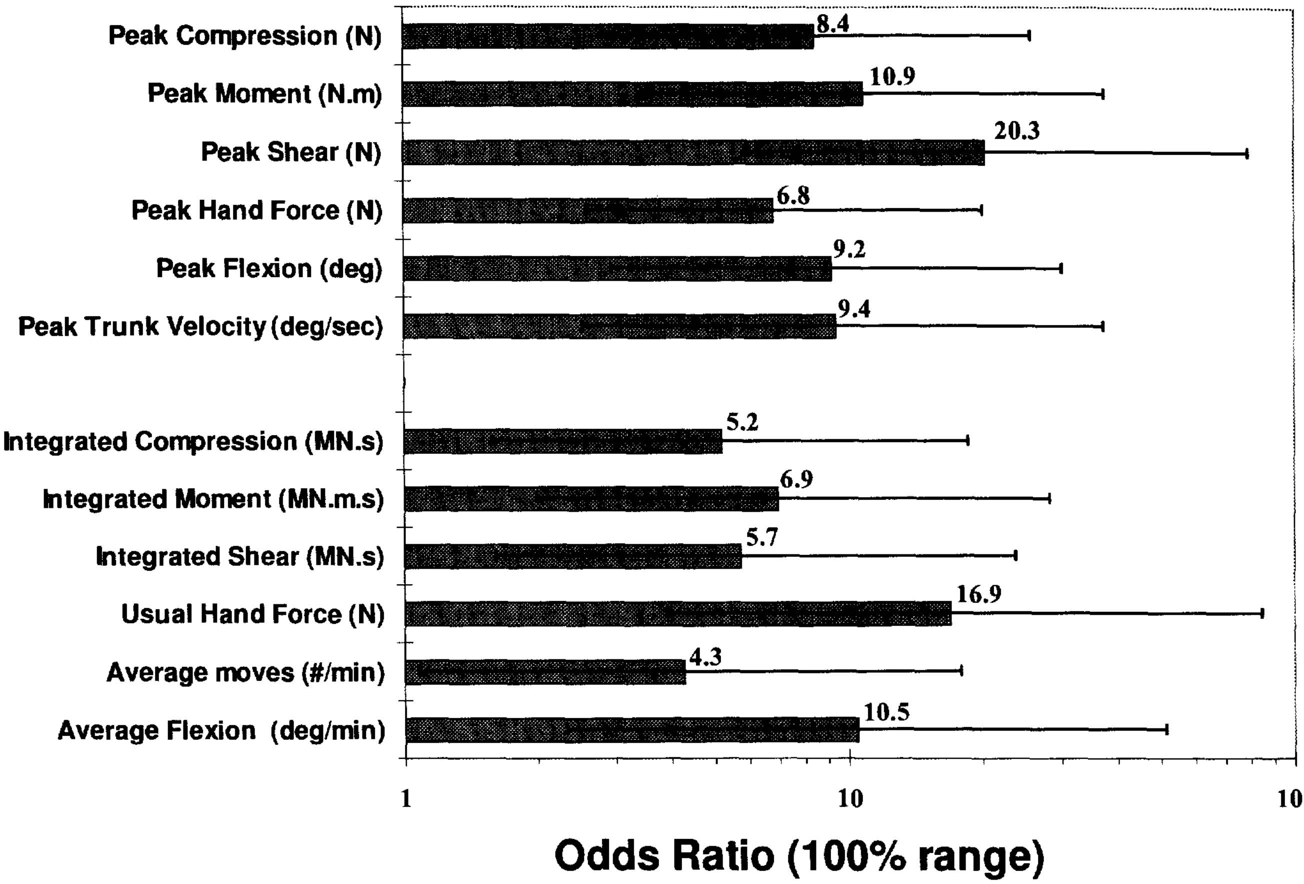

Fig. 1. Odds ratios and 95% confidence intervals calculated univariably for all 12 exposure variables. The odds ratios calculation was based on an exposure difference equivalent to 100% of the range of the randomly selected jobs in the plant.

Table 6
Multivariable logistic regression model resulting from a backwards selection procedure. Odds ratios (ORs) and 95% confidence intervals (CIs) are presented for exposure differences equal to both the inter-quartile spread (conservative) and full range (maximum risk) as seen in the randomly selected jobs in the manufacturing plant. Estimates of combined risk can be obtained by multiplying the relevant odds ratios

Variable	Inter-quartile spread			100% Range		
	IQS	OR	95% CI	Range	OR	95% CI
Peak shear (N)	203	1.5	1.0–2.4	727	4.7	1.0–22.6
Peak trunk velocity (deg s^{-1})	22.6	1.6	1.1–2.5	81.4	5.8	1.3–26.7
Integrated moment (MN m s)	0.21	1.4	1.0–2.0	0.88	4.5	1.1–21.0
Usual hand force (N)	70	1.7	1.2–2.6	314	10.5	1.9–65.6

tions to the study. The variables that emerge in a study of this nature depend on what it measured, how well it is measured and how one defines case and control group classification. An analysis of some of these limitations follows.

About 30% of the control subjects reported some back pain to the research staff but had not reported it to a nursing station in the previous 90 days; therefore, they remained classified as controls. Furthermore, this study is about reported pain, not medically diagnosed pathology. Although all participants did receive a simple clinical examination by a trained, non-clinical researcher during an in-home interview regarding psychosocial factors, no specific medical diagnosis was required to be a case. Including subjects in the control group who had LBP but had not reported it to the nursing station could have resulted in misclassification of some of the controls, an error that would likely result in underestimates of the true effect sizes for the observed ORs. On the other hand, the results of the study are, perhaps, more representative of the full workforce than if a large number of the potential controls had been excluded because of 'mild' back pain. Moreover, the pain reported by the cases did not have to result in time lost from the job. The only basic criterion for eligibility for both cases and controls was no previous LBP report in the previous 90 days. Consequently, the inclusion criteria for both cases and controls were far from stringent. However, analysis of the clinical data indicated that cases were representative of patients seen in primary care for treatment of routine LBP. While cases and controls were different in their LBP status, weak inclusion criteria would tend to narrow any differences in sizes of exposure measures between cases and controls and reduce ORs.

Nearly 20% of the data that were entered as 'case' biomechanical data were, in fact, obtained on 'job-matched control' proxies. Punnett *et al.* [3] reported that this method, which elevates statistical power by increasing the case sample size, did not affect their conclusions unreasonably. Analysis of the biomechanical data of the proxy participants in the present study showed that they tended to fall between the values of the cases and those of the random controls. Therefore, while the proxy data tended to narrow gaps in exposure levels between cases and controls, imprecision in the data would, again, have the effect of reducing rather than inflating the ORs.

The estimates of forces on spinal tissues entered into logistic regression procedures were specific to the spine model used and the question of validity of spine models frequently arises. In the opinions of the biomechanists on the study team, none of the spine models that have been presented to data in the literature have been directly validated by comparing model estimates of muscle force, spinal compression or shear with direct, in vivo measures of these same variables in the same units of measurements. Technically, this type of validation is currently not possible. Consequently, anatomical and physiological content validity in the structure and function of these types of models are important. An attempt has been made to incorporate as much content validity as possible into the spine model used in this study, but assumptions and simplifications are present in all models. This problem notwithstanding, calculations of forces on spinal tissues were made using the same biomechanical spine model on all participants.

Perhaps a more serious limitation is that a two-dimensional rather than a three-dimensional spine model was used, even though the model could handle asymmetric, dynamic forces on the hands. Moments, compression and shear attributable to lateral bend or pure spinal torsion were not calculated for the data presented and the values entered into the statistical model were undoubtedly underestimates of the sizes of these variables in tasks in which this type of loading was present. In addition some overestimation of compressive forces would have occurred in tasks in which the inertial forces on the hands were large since the quasi-dynamic model produces larger compressive estimates than a fully dynamic model used to estimate the same lifting tasks [18].

Despite error in model assumptions, the utilization of a two- rather than a three-dimensional model and a quasi-dynamic rather than a fully dynamic model, both cases and controls are treated statistically equally since the same model was used on all participants. The model outputs proved to be able to distinguish differences in loading on spinal structures between cases and controls, identifying statistically significant risk factors. In this sense, the biomechanical spine model used in this study has been validated for its ability to produce an estimate of risk of LBP.

The computerized video posture program that was developed and used for the kinematic variables was capable of recording lateral bend and spinal torsion, but these variables did not produce significant univariable ORs in this study, unlike the findings of Marras *et al.* [2] and Punnett *et al.* [3]. Therefore, they were not used in the data base analyzed here. It is possible that our measures of non-sagittal trunk kinematics were not as good as those of Marras *et al.* [2] who used an electrogoniometer approach. However, both our computerized video system and the type of work analyzed were similar to those of Punnett *et al.* [3]. It is worth noting that the interobserver agreement was better for sagittal kinematics than lateral bend or twist [17].

The measurement of sizes and directions of forces on the hands in field studies is always difficult. Whenever possible, force transducers were used. Assessment of direction required the judgment of observers. They were extensively trained but any subjective judgment is error prone. Workers simulated efforts against the force transducers when they could not be inserted between their hands and the tool or material. Discrepancies between the actual force applied on the job and the worker estimates during the simulations of effort are probably present but are unlikely to have been differentially biased for cases and controls.

In spite of the limitations discussed above, these results have shown that cases experienced significantly higher biomechanical loading than controls in all variables. Differences in univariable ORs among exposure variables suggest that some measures are more sensitive than others in distinguishing cases from controls. All of the ORs calculated in this data set were statistically significant. Peak shear and peak torso flexion showed high ORs for both the IQS and 100% range data. Hypothesis no. 1 is, therefore, supported: there are physical work exposure variables that distinguish people who have reported LBP (cases) from those who have not (controls), but with varying predictive strength.

There is considerable evidence to support hypothesis no. 2: that there are variables that characterize ‘cumulative exposure’ to load that provide information about LBP that is different from ‘peak load’ variables. All of the cumulative loading variables were significantly higher for the cases than for the controls and showed substantial univariable ORs at both the IQS and 100% range unit values.

The low correlations between the peak and corresponding cumulative measures of compression, shear and moment show that the integrated data are not simply a result of multiplying peak values linearly by time to obtain the integral or dividing by time to obtain an average. These variables are, apparently, measuring different demands of the jobs. Moreover, in the multivariable analysis only one of the peak and one of the cumulative spine loading variables entered any one model. This suggests that peak and cumulative or time-averaged loading variables are also measuring different aspects of risk. This cannot be said for the external load (hand force) and kinematic variables. These variables showed much higher correlations between the peak and cumulative versions and a peak or a cumulative version of the variable, not both, showed up in the multivariable logistic regression analyses as mutually exclusive risk factors, in addition to the ’peak spine load’ and ‘cumulative spine load’ factors.

Further support for hypothesis no. 2 is evident from the factor analysis which clearly showed a ‘cumulative loading’ factor that was different from a ’peak loading’ factor. Therefore, hypothesis no. 2 is supported by results of the analysis of the three spinal tissue loading variables; spinal compression, shear and moment. Spinal moment, one could argue, is a close analog of tissue loading since the external moment is supported primarily by lumbar muscle fascicles if the lordosis is maintained and by muscle and ligament or ligament if the lordosis is partly or completely lost [23, 24].

No distinction was possible in this study between cumulative loading that is the result of high repetition and that which was the result of prolonged duration. It would have been useful to have been able to separate these because their potential injury-inducing pathways are probably different. The former may result in repetitive micro-trauma of tissue, the latter in excessive strain on tissue because of creep.

Hypothesis no. 3 was not supported; all four types of variables showed substantial associations with risk of LBP reporting. While peak spinal loading tended to account best for differences between cases and controls, the ORs associated with all of the variables were both statistically significant and similar in magnitude. The factor analysis convincingly showed that there were not only peak and cumulative spinal tissue loading factors but that the external forces on the hands and the kinematic variables were sufficiently independent of these factors and from each other to appear as separate risk factors. This independence is confirmed by the multivariable logistic regression analysis which identified one variable from each of the four factor groupings. Therefore, hand forces and trunk kinematics are not merely surrogates for the biomechanically modelled spinal tissue loads; these variables are contributing information about risk of LBP that is different from the information contributed by the estimates of load on spinal tissues. Conversely, output from the biomechanical spine model provided information that was different from the inputs of trunk kinematics and forces on the hands, justifying the continued use of these models to assess risk of LBP.

The factor interpretation in Table 4 is not an output of the analysis. Factor titles were based upon both the variables loading heavily on the factor and the low back exposure constructs present in the literature. The individual factor loading weights for each variable indicate how strongly the variable correlated to the corresponding factor. The largest factor loading weight for each variable in Table 4 is indicated in bold and is the primary loading factor for that variable. The factors were then named according to which variables had their primary loading on that factor.

Peak flexion level, peak flexor velocity, the average moves per minute, and average degrees moved per minute all correlated strongly as factor 1, which we called Trunk Kinematics. These exposure variables have been used by many authors under names such as postural load, trunk angle, trunk flexion, repetitiveness and dynamic trunk motion. Factor 2 had primary loading from the peak compression, peak moment, and peak shear variables; this factor was called Peak Spinal Load. This is perhaps the most commonly used exposure measure for occupational biomechanics studies and has been reported by many authors (see for example [12,15,18]). Factor 3 had primary loadings exclusively from the integrated spine load variables and was named Cumulative Spinal Load. The notion of potentially harmful effects of excessively prolonged loading is quite common yet it is not frequently used as an exposure measure. Both the peak hand force and the usual hand force loaded primarily on the fourth factor, called Hand Force. The amount of total variance accounted for by the factors decreases as we move away from factor 1 to factor 4 in Table 4. The exposure variables have extremely high loading with the four main factors identified and only minor loading on the other factors. A few variables have non-trivial loading on more than one factor; Peak Flexion Angle, for example, contributes to factors 1 and 2. Extreme trunk flexion increases the lumbar moment and, thus, the spinal load so this intercorrelation is not surprising. The four factors that described the 12 peak and cumulative exposure variables accounted for 89% of the total variance.

The factor analysis results can be used to help interpret the multivariable logistic regression model. The final regression model included four variables; peak shear, peak flexor velocity, integrated moment and usual hand force. Examination of Table 4 shows that a representative variable from each of the four factors is in the regression model. This is to be expected because the multivariable model chooses variables with the strongest independent contributions to case-control status, while the factor analysis groups related variables into independent factors. Several other four-variable models were constructed which had similar power to predict case or control status. For example, substituting integrated compression for integrated moment resulted in a model with similar performance characteristics. In each case, however, the model would contain one variable from each factor, a clear indication of the important contribution each type of factor has to the risk of reporting LBP in the study site.

While all peak spine load variables were associated with the risk of LBP according to the univariable ORs, peak shear tended to remain in any multivariable model for which it was considered. Once this variable entered a logistic regression model any strongly correlated variables, such as peak moment and peak compression, were automatically excluded. The strong predictive power of the shear variable may be due to the responsiveness of shear to push and pull efforts. A push or pull effort performed at the waist (L_4/L_5) level will have little effect on the calculated moment and compression values but the shear will increase substantially under these forces. Push–pull efforts are common in an automotive assembly plant and in most other manufacturing environments. On the other hand, in the tasks observed, when the moment at L_4/L_5 was high, both compression and shear were high. There was very little pure axial loading that would produce high spinal compression but low shear. It is, therefore, more common for shear to be a factor both in the presence and in the absence of high compression or moment than the other way around. As a result, peak shear may be able to account for more of the case-control differences than peak compression or peak moment.

Kumar [6] reported differences in accumulated lumbar shear forces between institutional aides with and without back pain. Beyond this study, the authors are unaware of other studies that have epidemiological evidence that identifies shear forces as a risk factor for LBP. There are several biomechanical reasons why anterior shear of the superior lumbar vertebra on the inferior vertebra might result in at least irritation of inflamed tissues, if not observable tissue damage. McGill and Norman [23] and Potvin *et al.* [24] showed up to threefold increases in shearing forces supported by the facets, the annulus of the disc and posterior intervertebral ligaments if the lumbar extensor muscles were inactivated as a result of excessive torso flexion. Muscle activity, produced as long as the lumbar lordosis is maintained, reduces the size of the shear forces supported by other spinal structures. In extreme anterior shear loading, the pars interarticularis fractures but in the intact spine the disc sustains the largest portion of the anterior shear load [26]. Krypton *et al.* [27] also produced disc damage as well as facet and lamina fractures in shear loading of facet joints and deformation of annular fibres in the disc could conceivably result in pain in people who, for example, might have already sustained micro-trauma or have pre-existing inflammation of structures that must support shear forces. Free nerve endings have been shown in these spinal structures in rabbit and human specimens [28,29].

There are many reports from in vitro studies of damage to spinal structures arising from excessive peak forces [15,30]. There are some epidemiological studies of biomechanical risk factors that have shown that peak kinematic variables, such as torso angles beyond 20° [3] or torso velocities above certain values [2], can distinguish workers who report LBP from those who do not or those who work on 'high risk' jobs from those in jobs of lower risk. In addition, Herrin *et al.* [1] and Marras *et al.* [2] showed that some peak kinetic variables, spinal compression and lumbar reaction moment of force, were also able to distinguish workers in high injury incidence jobs from those in jobs of lower injury incidence. These three epidemiological studies of low back troubles all involved large numbers of participants and extensive data collection but used relatively short durations of worker monitoring (a few minutes or a few job cycles) and the recording of 'peak' rather than 'cumulative' loading variables. Analyses in all these studies showed statistically significant odds ratios or significant relationships between the size of the biomechanical exposure measures and LBP incidence.

The present study supports the general findings of these studies, that biomechanical loading is a strong risk factor in the reporting of work-related LBP. In addition, this study documents the importance of cumulative loading and strongly points to the importance of shear forces acting on the lumbar spine as risk factors. Another paper will show that these findings hold after accounting for the effects of psychosocial variables such as perceptions of job control, the workplace social environment and job satisfaction.

8. Conclusions

There are a number of limitations of this study. In particular, the following should be noted: the relatively weak criteria for classification of 'cases' and 'controls'; the use proxies for almost 20% of the biomechanical data to represent cases; logistical problems and measurement error in taking biomechanical methods out of the laboratory to obtain detailed measures in the field on more than 200 participants for observation periods ranging from two to eight hours. All of these limitations would tend to make it harder to find differences between cases and controls which, perhaps, attests to the robustness of the findings. Based upon the data presented in this paper, the following conclusions about biomechanical risk factors for reported LBP in an auto assembly facility seem to be justified:

1. Biomechanical work-exposure variables are strongly associated with the risk of reporting LBP at work, but with varying strength of association across different variables.
2. Cumulative spinal load per shift provides information that is different from peak spinal load in distinguishing those who report LBP in the workplace from those who do not.
3. Estimates from a biomechanical spine model of spinal compression, shear and torso extension moment of force at L_4/L_5, regardless of whether they are peak or cumulative loading estimates, while separating cases from controls, are not always better able to do this than kinematic and external loading variables.
4. Four factors emerged to distinguish cases from controls; peak spinal load, cumulative spinal load, kinematic variables related to torso motion involved in the job, and external forces on the hands. Trunk kinematics and external force variables are not merely 'surrogates' of spine tissue loading estimates from biomechanical models. They provide information about LBP risk that is different from that provided by the tissue loading estimates even though they are inputs to the spine model. Conversely, outputs from the spine model provide risk factor information that is different from that of the inputs to the model alone and are useful exposure measures.
5. There is more than sixfold increase in the risk for reporting LBP for workers with high levels of exposure to all four major risk factors indentified: peak shear; integrated lumbar moment over the duration of the shift; peak torso flexion velocity; and usual hand force over the course of the shift.
6. Although the best statistical model included the combinations of variables listed in no. 5, above, very little predictive power was lost by substituting variables such as spinal compression or moment, which were eliminated from the 'best' multivariable model because of high correlation with spinal shear force. It would, therefore, be unwise to dismiss compression or moment as risk factors only because they did not emerge in the best multivariable statistical model.

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