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SPECIAL ISSUE: Epidemiological Studies of Workplace Musculoskeletal Disorders

The NIOSH Lifting Equation and Low-Back Pain, Part 1: Association With Low-Back Pain in the BackWorks Prospective Cohort Study

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Objective: The aim of this study was to evaluate relationships between the revised NIOSH lifting equation (RNLE) and risk of low-back pain (LBP).

Background: The RNLE is commonly used to quantify job physical stressors to the low back from lifting and/or lowering of loads. There is no prospective study on the relationship between RNLE and LBP that includes accounting for relevant covariates.

Method: A cohort of 258 incident-eligible workers from 30 diverse facilities was followed for up to 4.5 years. Job physical exposures were individually measured. Worker demographics, medical history, psychosocial factors, hobbies, and current LBP were obtained at baseline. The cohort was followed monthly to ascertain development of LBP and quarterly to determine changes in job physical exposure. The relationship between LBP and peak lifting index (PLI) and peak composite lifting index (PCLI) were tested in multivariate models using proportional hazards regression.

Results: Point and lifetime prevalences of LBP at baseline were 7.1% and 75.1%, respectively. During follow-up, there were 123 incident LBP cases. Factors predicting development of LBP included job physical exposure (PLI and PCLI), history of LBP, psychosocial factors, and housework. In adjusted models, risk (hazard ratio [HR]) increased per-unit increase in PLI and PCLI (p = .05 and .02; maximum HR = 4.3 and 4.2, respectively). PLI suggested a continuous increase in risk with an increase in PLI, whereas the PCLI showed elevated, but somewhat reduced, risk at higher exposures.

Conclusion: Job physical stressors are associated with increased risk of LBP. Data suggest that the PLI and PCLI are useful metrics for estimating exposure to job physical stressors.

Keywords: epidemiology, ergonomics, occupational cohort, job analysis, risk assessment

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INTRODUCTION

Low-back pain (LBP) is a common health problem in the general population, affecting 80% to 85% of people in their lifetime (World Health Organization, 2003) and is a frequent cause of activity limitation (Bigos, Bowyer, & Braen, 1994; Walker, Muller, & Grant, 2004). According to the Bureau of Labor Statistics (2011), musculoskeletal disorders (MSDs) accounted for 29% of all injuries and illnesses requiring days away from work in 2010. Back was injured in nearly half of the MSD cases and required a median of 7 days to recuperate (Bureau of Labor Statistics, 2011). In 2011, average claim cost for a back injury was approximately $8,400 (Dunning et al., 2010; Washington Department of Labor & Industries, 2011).

LBP literature suggests multifactorial risk factors, with many possible etiologies (Manchikanti, 2000). Suggested LBP risk factors include (a) job physical factors, (b) worker demographics, (c) past LBP history, (d) psychosocial factors, and (e) hobbies and physical activities outside of work (Hayden, Chou, Hogg-Johnson, & Bombardier, 2009; Manchikanti, 2000). Peak prevalence of LBP occurs between 45 and 64 years of age (Deyo & Tsui-Wu, 1987; Papageorgiou, Croft, Ferry, Jayson, & Silman, 1995; Riihimaki, 2000), gender has little effect on prevalence of LBP (Deyo & Tsui-Wu, 1987; Walker et al., 2004), and being overweight or obese has a weak association with increased risk of LBP (Leboeuf-Yde, 2000; Shiri, Karppinen, Leini-Arhas, Solovieva, & Viikari-Juntura, 2009). Past history of LBP is consistently associated with LBP (Hincapie, Cassidy, & Cote, 2008; Matsudaira et al., 2012; Nelson & Hughes, 2009; Tubach, Leclerc, Landre, & Pietri-Taleb, 2002). Low work support, low job satisfaction, and/or high work demand appear to have more consistent association with LBP compared with other workplace psychosocial factors (Hoogendoorn, van Popel, Bongers, Koes, & Bouter, 2000; Macfarlane et al., 2009; Matsudaira et al., 2012; Papageorgiou et al., 1997; Tubach et al., 2002; Van Nieuwenhuyse et al., 2004).

Authors of several studies have reported associations between job physical factors and LBP (Hartvigsen, Bakketeig, Leboeuf-Yde, Engberg, & Lauritzen, 2001; Hoogendoorn, Bongers, de Vet, Ariens, et al., 2002; Marras, Lavender, Ferguson, Splittstoesser, & Yang, 2010; Matsudaira et al., 2012; Norman et al., 1998; Tubach et al., 2002; Vandergrift, Gold, Hanlon, & Punnett, 2012; Waters, Lu, Piacitelli, Werren, & Deddens, 2011). However, precise associations are not clear due to different measures of biomechanical stressors used in past studies. Further, there is lack of consensus on the exact roles of individual, psychosocial, and biomechanical factors in the genesis of LBP (Hartvigsen et al., 2001).

Previous investigations on association between job physical factors and LBP either were cross-sectional, relied on self-reported physical exposure, or did not account for confounding by individual and psychosocial factors (Chaffin & Park, 1973; Garg & Chaffin, 1975; Harkness, Mcfarlane, Nahit, Silman, & Mcbeth, 2003; Hartvigsen et al., 2001; Herrin, Jaraiedi, & Anderson, 1986; Hoogendoorn, Bongers, et al., 2000; Hoogendoorn, Bongers, de Vet, Twisk, et al., 2002; Liles & Mahajan, 1985; Marras et al., 1993; Matsudaira et al., 2012; Norman et al., 1998; Plouvier, Leclerc, Chastang, Bonenfant, & Goldberg, 2009; Tubach et al., 2002; Van Nieuwenhuyse et al., 2006; Vandergrift et al., 2012; Waters et al., 2011). A few prospective cohort studies of job physical factors have controlled for the effects of individual and/or psychosocial factors. However, these studies have either measured a single job physical exposure variable (e.g., trunk flexion, trunk rotation, lifting, heavy weight) or relied on self-administered questionnaires or structured interviews to estimate biomechanical stressors (Harkness et al., 2003; Hoogendoorn, Bongers, de Vet, Ariens, et al., 2002; Hoogendoorn, Bongers, de Vet, Twisk, et al., 2002; Jansen, Morgenstern, & Burdorf, 2004; Plouvier et al., 2009; Tubach et al., 2002; Vandergrift et al., 2012).

Researchers who use a single job physical exposure variable to quantify biomechanical stressor may ignore potential interactions between job physical exposure variables. Use of a self-administered questionnaire may lead to biases or errors in classifying categories of physical exposure. Possibly because of these reasons, a recent review of prospective cohort studies concluded that the evidence for association between LBP and either (a) heavy physical work or (b) working with trunk bent and/or in a twisted posture was conflicting (Bakker, Verhagen, van Trijffel, Lucas, & Koes, 2009).

The revised NIOSH lifting equation (RNLE; Waters, Putz-Anderson, Garg, & Fine, 1993, 1994) is a job analysis method commonly used to quantify biomechanical stressors to low back from lifting and lowering of loads in workplaces (Kucera et al., 2009; Mirka, Kelaher, Nay, & Lawrence, 2000; Russell, Winnemuller, Camp, & Johnson, 2007; van der Beek, Mathiassen, Windhorst, & Burdorf, 2005; Waters, Putz-Anderson, & Baron, 1998). The RNLE combines seven biomechanical stressors (weight of the object, horizontal location, vertical location, travel distance, twisting angle, frequency and duration of lifting, and type of grasp) into a single metric to quantify biomechanical stressors. This metric is called the lifting index (LI) for simple tasks and composite lifting index (CLI) for complex tasks (Waters et al., 1994). Authors of a few investigations, mostly involving cross-sectional studies, have reported an association between the LI and LBP (Boda, Garg, & Campbell-Kyureghyan, 2012; Marras, Fine, Ferguson, & Waters, 1999; Waters et al., 1999, 2011). There is no prospective study on the relationship between RNLE and LBP that includes accounting for relevant covariates.

This study's hypothesis is that there is a relationship between job physical factors, measured by the RNLE, and risk of developing LBP.

METHOD

This study was approved by the University of Wisconsin–Milwaukee Institutional Review Board (#04-02-049).

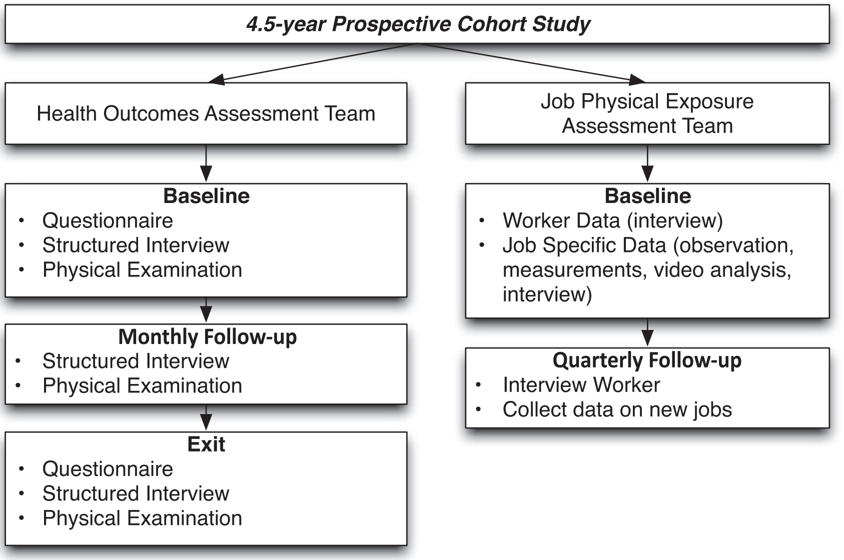

Figure 1. Data collection sequencing.

Workers for the study were recruited from 30 diverse facilities located in four states (Illinois, Texas, Utah, and Wisconsin). Workers at these facilities performed a variety of operations, including (a) poultry and meat processing; (b) baking; (c) printing; (d) order selection in grocery warehousing; (e) clothing, book packaging, and palletizing in a distribution center; and (f) manufacturing of automotive parts, airbags, lawnmowers, small engines, cabinets, glass windows and doors, metal parts, plastic parts, electric lights, office chairs, salt, chemicals, cosmetics, and ice cream.

In all 30 facilities, the research team had an opportunity to explain the study and invite workers to participate during open meetings. A total of 897 of 1,240 workers attending (72%) consented to participate (overall participation rate is unclear as the researchers had access only to those willing to attend the open meetings, although it is believed to be more than 50%). All production workers were eligible to participate in the study except those with unpredictable changes in job physical exposures or for whom it was not feasible to quantify physical exposure (e.g., supervisors, clerical workers, maintenance or mechanics, and forklift truck drivers).

Two teams, blinded to one another, collected health outcomes and job physical exposure data at baseline and throughout the follow-up period. Figure 1 depicts the sequencing of data collection.

Worker Health, Demographics, Hobbies, Physical Activities, and Psychosocial Data Collection and Assessment

At baseline, the health outcomes team administered a questionnaire, structured interview, and physical examination. The questionnaire and structured interview were laptop administered by physical therapists and included information on (a) worker's demographics (e.g., age, gender, race, and education level), (b) hobbies and outside of work activities (including frequency and duration of these), (c) intensity (rated on a 0-to-10 numeric rating scale) and duration (expressed as percentage of time symptomatic during the prior month) of LBP at or 1 month prior to baseline, (d) medical history (including lifetime LBP history [defined later], other musculoskeletal disorders [MSDs], high blood pressure, high cholesterol, rheumatoid arthritis, lupus, osteoarthritis, degenerative arthritis, fibromyalgia, osteomyelitis, osteoporosis, broken bones, and other relevant diseases), (e) psychosocial questions (modified APGAR; Bigos et al., 1991; a measure of coworker and supervisor support [seven questions]; a subset of questions from the Zung Depression Scale; Zung, 1965 [eight questions; see appendix]; and a composite Tense-Edge-Nervous Scale [three questions; see appendix] developed for this study), and (f) a few other questions (e.g., smoking, alcohol consumption, blood relatives with LBP). For the purpose of this study, LBP history was defined as LBP resulting in (a) workers' compensation, (b) lost time, (c) light duty, or (d) visit to a health care provider and/or (e) LBP radiating down the leg(s).

A standardized physical examination of the back was performed by the same therapist who administered the structured interview. The medical examination focused on the presence or absence of physical signs and provocative maneuvers related to the low back, such as (a) tender points, (b) tendon reflexes, (c) recumbent and seated straight leg raise, (d) sacroiliac joint test, (e) inspection for evidence of scar or surgery, and so on. However, findings from the physical examinations were not used in this study. Heights and weights were measured to calculate body mass indices (BMI).

During the monthly cohort follow-up, new symptoms of LBP during the past month, and changes in these symptoms, were recorded with a structured interview.

LBP Case Definition

An incident case of any LBP was defined as regional LBP in lumbosacral area, of any pain intensity, and lasting at least 1 day. Those with prior LBP were eligible to become an incident case provided they had a continuous pain-free period of at least 90 days at the time of enrollment. Workers who had past surgeries (fusion, laminectomy, laminotomy) or baseline diagnosis or history of sciatica were excluded from becoming incident cases. During follow-up, those workers who reported that their episode of LBP was due to an accident were right censored as noncases 1 day prior to their accident.

Job Physical Exposure Data Collection

Job physical exposure data were individualized and measured at baseline by ergonomic analysts who had been trained and standardized. Job information and rotation schedules were obtained through interviews with the workers and their supervisors by asking them how many different tasks each worker performed and the duration of each task. Data were collected for each task and included (a) duration of each task and length of a work shift through worker and supervisor interviews, (b) object weights (according to digital platform scale), (c) pushing and pulling forces (force gauge, Model No. CSD250, manufactured by Chattilon), (d) horizontal and vertical hand locations at origin and destination of lift or lower (tape measure; Waters et al., 1994) (e) push/pull and walk/carry distances (rolling tape measuring device), (f) duration of task activities (digital stopwatches), and (g) videotaping. Each task performed by the worker was videotaped for at least 15 min without interrupting the worker. Tasks with cycle time ≤5 min were recorded for at least five cycles, and tasks with cycle time >5 min were recorded for 20 to 45 min, ensuring at least one complete cycle was recorded. Video was taken perpendicular to the sagittal plane to facilitate biomechanical analyses performed in laboratories. In those cases in which direct measurements could not be taken (no interruption of worker, a confined area), video was taken from a variety of angles so that tasks could be simulated in the laboratory and hand locations estimated.

Videos were analyzed at a rate of three frames per second to determine (a) cycle time, (b) frequency of lifting and lowering, (c) type of grasp, (d) travel distance, and (e) asymmetric angle (Waters et al., 1994).

Trained ergonomics analysts visited each worker every 3 months to assess job physical exposure changes. If either a worker or a supervisor reported a change in the job, physical exposures were reassessed with use of the same protocol used at baseline.

RNLE Analyses

LI and CLI were computed for each subtask and task that a worker performed at baseline as well as for those tasks that changed during the follow-up period. Using Waters et al. (1994) methodology, we calculated LI for each unique combination of weight, horizontal and vertical location of hands, travel distance, grasp, asymmetric angle, and frequency of lifting and lowering both at origination and destination (subtask). We computed CLI for each task from LIs for subtasks using the procedure recommended by Waters et al. (1994). The CLI included all lifts and lowers performed in a task. For example, for grocery warehouse order selectors, task was one order and that task included all lifts and lowers performed in that grocery order. Within a task, an LI was calculated for each unique combination of object weight, horizontal location, vertical location, travel distance, and type of grasp. In those situations in which lifts or lowers exceeded Waters et al.'s (1994) recommended values, the corresponding multipliers were capped at their maximum penalties (e.g., horizontal multiplier was capped at 0.4 for horizontal distances greater than 63 cm). We treated LIs and CLIs as continuous variables. Then, using the Waters et al. (1994) prescribed cut points, we classified LI score into one of the three categories: LI ≤ 1.0, $1.0 < \text{LI} \leq 3.0$, and LI > 3.0. The same procedure was used to classify CLI.

Assigning Exposure at the Worker Level

Forty-five percent of workers performed more than one task during their workday or had job rotation. As there is no consensus method to quantify job exposures for a worker who performs two or more tasks (Garg & Kapellusch, 2009a, 2009b), "peak exposure" was used to assign worker exposure (Boda et al., 2012; Herrin et al., 1986; Marras et al., 1993). Peak LI (PLI) was defined as the highest LI from all subtasks performed by a worker. Similarly, peak CLI (PCLI) was defined as the highest CLI from all tasks. Table 1 summarizes exposure variables and metrics used to quantify job physical exposure.

Statistical Analyses

The baseline and lifetime prevalence of LBP was determined. Those workers with LBP in the past 90 days at baseline were subsequently excluded from analyses. Time from enrollment into the study to first event of LBP was modeled with the use of Cox proportional hazard (PH) regression (Cox, 1972). To account for changes in job physical exposure during follow-up, unadjusted univariate hazard ratios (HR) for incident cases of LBP and 95% confidence intervals for PLI and PCLI were determined with the use of time-varying covariates. All other covariates, such as age, gender, BMI, hobbies, psychosocial factors, and past medical history, were treated as time-independent covariates (see Table 2). We performed analyses using the coxph() function in R-64 Version 2.13.1 for Macintosh (R Development Core Team, 2011). The statistical procedure used in the current study was similar to that used by Garg et al. (2012).

The functional form of each continuous variable (age, BMI, LI, and CLI) was determined from Martingale residual plots (Therneau, Grambsch, & Fleming, 1990). The null PH model was fit and the resulting Martingale residuals were plotted against each of the four continuous variables. Smoothed plots of the residuals provided approximate shapes of the covariate (Therneau et al., 1990). As different smoothing methods may suggest different functional forms (Lin, Wei, & Ying, 1993), we examined loess curves and cubic smoothing splines as flexible means for estimating the shape (Ruppert, Wand, & Carroll, 2003). Results were consistent between smoothing methods.

No transformation was suggested for the three psychosocial scales (modified APGAR, modified Zung, and Tense-Edge-Nervous); however, age, BMI, PLI, and PCLI all exhibited a strong linear trend in the midregions followed by either a smaller upward trend, a leveling off, or a downward trend for the remaining values. To model the nonlinearity in the upper region suggested by these plots, we included a linear spline term with a knot, which gives the univariate PH model: $\log(\text{HR}) = b_1 x + b_2 (x - K)_+$, where x is the continuous variable of interest and the knot, K, was selected to be at approximately where the downward turn (inflection point) occurred in the residual plot. We used the closest quantile of cases to the inflection point as the knot (i.e., the 50th percentile for age, 75th percentile for BMI, 20th percentile for PLI, and 30th percentile for PCLI). The "plus" notation on the spline term, $(x - K)_+$, indicates that this term is zero when $x - K \leq 0$. In simple terms, these linear splines are two line segments connected by a single point (called a knot). The slopes of the line segments were allowed to be different, thus allowing for a nonlinear relationship between PLI or PCLI and risk of LBP, measured as log(HR).

TABLE 1: Summary of Job Physical Exposure Variables and Metrics From Peak Exposure

Variable(s)	Source	Reference
Object weight (W)	Field measurement	—
Horizontal location of hands (H)	Field measurement	Waters, Putz-Anderson, Garg, & Fine (1994)
Vertical location of hands (V)	Field measurement	Waters et al. (1994)
Travel distance (D)	Video analysis	Waters et al. (1994)
Cycle time (s)	Video analysis	—
Lifts or lowers per minute (F)	Video analysis	Waters et al. (1994)
Type of grasp (C)	Video analysis	Waters et al. (1994)
Asymmetric angle (A)	Video analysis	Waters et al. (1994)
Duration of task (hours per day) (HD)	Worker/supervisor interview	—
LI calculated with variables W, H, V, D, A, C, F, HD	Calculated	Waters et al. (1994)
CLI calculated with variables LIs, Fs, HD	Calculated	Waters et al. (1994)

Note. LI = lifting index; CLI = composite lifting index.

Multivariate models were built to test whether PLI and PCLI were associated with increased risk of LBP after controlling for potential confounders and/or effect modifiers (covariates). Potential covariates were those nonphysical exposure factors that (a) were not collinear, (b) were biologically plausible, and (c) had a univariate p value $\leq .20$. All covariates were treated as time independent and formed a pool of candidate variables for inclusion in the final covariate model. Physical exposure variables (PLI and PCLI) were withheld during the covariate model building process. The final covariate model was determined with the use of a best subsets variable selection procedure with the corrected Akaike information criterion (AICc score; Collett, 2003; Hurvich & Tsai, 1989). Age, gender, and BMI were forced into every covariate model.

Martingale residual plots from this final covariate model were examined to check the functional form of each exposure variable of interest (PLI and PCLI) and these were consistent with the forms suggested by the null model residual plots. Separate multivariate models were then fit for the PLI and the PCLI using their respective linear spline functional forms. Subsequently, the categorical forms of PLI and the PCLI (Waters et al., 1994) were forced into the covariate model.

RESULTS

Workers were recruited during the first 12 months of the study. Out of 897 workers initially enrolled, 574 workers (64%) completed baseline data collection (Figure 2); 323 of the initially enrolled workers were lost, primarily due to participating plants closing. Out of 574 baseline workers, 551 had at least one follow-up visit. Out of those 551 workers, 37 workers were excluded due to baseline diagnosis of sciatica ($n = 21$), low-back surgeries ($n = 15$), and upper-limb deformity ($n = 1$). Thus, the follow-up cohort had 514 workers. Out of those 514 workers, 256 had LBP within 90 days at baseline and were considered baseline prevalent. Excluding those 256 workers, the LBP incident-eligible cohort for this study included 258 workers. The incident-eligible cohort was followed for a median of 10.6 months (average = 14.7 ± 11.8, range = 0.3 to 53.7). The median follow-up time was somewhat short, as 48% of the 258 incident-eligible workers became cases—some rather quickly—and stopped contributing time for this outcome. During the 4.5-year follow-up period, study participation decreased, primarily due to plant closings and layoffs.

Point, 3-month, and lifetime prevalence of LBP at baseline, among the 514 followed workers described previously, were 21.0%, 49.8%,

TABLE 2: Potential Confounders and/or Effect Modifiers Considered for Multivariate Analyses of Lower-Back Pain (LBP)

Demographic	**Psychosocial**
Age	Modified APGAR (7 questions)
Alcohol consumption	Modified Zung (8 questions)
Currently smoke	Tense-Edge-Nervous (3 questions)
Ever smoked	Recommend job to others
Gender	Would take their job again
Marital status	**Hobbies and activities**
Time to commute to work	Aerobics
Total miles travelled/day	Baseball
Anthropometric	Basketball
Body mass index	Bicycling
Hip circumference	Fishing
Waist circumference	Football (American)
Socioeconomic	Gardening
Education level	Housework
Race	Hunting
Past medical history	Knitting
Diabetes mellitus	Maintenance
Fracture	Motorcycling
Gout	Racquetball
Hernia	Remodeling
High blood pressure	Running
High cholesterol	Snow shoveling
Kidney failure	Snow skiing
Osteoarthritis	Snowmobiling
Rheumatoid and other Inflammatory arthritis	Tennis
Thyroid problem	Swimming
Past LBP history (pain radiating to leg[s], sought health care, lost time, modified duty, and/or received workers' compensation for LBP)	Walking
	Weight lifting
	Woodworking
	Yoga

and 75.1%, respectively. Among the 258 incident-eligible workers, there were 123 new LBP cases (n = 41, 48.2% of females, and n = 82, 47.4% of males) during the 4.5 years of follow-up, resulting in an incident rate of 39.5 cases per 100 person-years. Females and males had about the same LBP incidence rate, 38.7 versus 39.9 per 100 person-years, respectively. A majority of cases (105) believed their LBP was either work related (65 cases) or of an "unsure cause" (n = 40). Eighteen cases believed their LBP was caused by something outside of work. The mean of peak pain ratings for the 123 incident cases was 4.9 ± 1.6 (range = 1 to 10, on a 10-point scale). Lumbar paraspinal region was the most common body region for LBP, with 72 cases experiencing pain only in this region and 91 experiencing pain in this and other regions. On the average, their pain lasted for 8.5 days (range = 1 to 120), ending either due to resolution

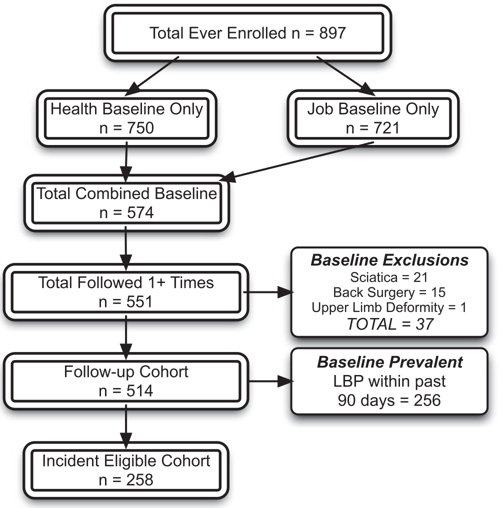

Figure 2. Subject enrollment and exclusion statistics.

of the pain, departure from the study, or the study concluding. Sixty-five workers had prior history of LBP, and out of these, 67.7% were incident cases.

Descriptive statistics for the incident-eligible cohort (n = 258) are summarized in Table 3. The mean age of the cohort was 37.1 ± 12.0 (range = 18.5 to 65.2) years. Most of the cohort were male (67.1%), and 76.0% were overweight (BMI = 25 to 29.9 kg/m^2) or obese (BMI ≥ 30.0 kg/m^2). Ten (3.9%) reported being diabetic and 37 (14.3%) had high cholesterol. A majority reported being physically active outside of work with participation in aerobic exercises and/or sports (61.2%). Most (83%) had one or more hobbies or activities, such as housework, gardening, snow shoveling, maintenance work, and/or woodworking.

Regarding variables used in the RNLE for calculation of PLI and PCLI, mean weight lifted per worker ranged from 0.9 to 44.3 kg, with overall mean of 9.3 ± 5.5 kg. Mean horizontal and vertical locations of hands per worker, at the origin of lift, were 37.6 ± 8.0 cm (range = 22.0 to 66.0 cm) and 86.6 ± 14.3 cm (range = 29.2 to 123.3 cm), respectively. Mean asymmetric angle per worker ranged from 0° to 39°, with overall mean of 5.7° ± 6.6°. Average lifting frequency per worker was 2.1 ± 2.0 lifts per minute (range = 0.1 to 14.0). Only a small percentage of workers (10.4%) had low job physical demands (PLI ≤ 1.0), and a substantial number of workers (25.6%) had very high job physical demands (PLI > 3.0) (Table 3).

It should be noted that descriptive statistics for job physical exposure variables (Table 3) were calculated from physical exposures in the first time period of observation (baseline). However, univariate analyses reported for job physical exposure variables in Table 4 included data from all observation time periods (time-varying covariates).

Univariate Results

Age, BMI, PLI, and PCLI were fit with linear spline functions with a single knot (K), resulting in two spline terms for each variable. Estimated HR for first spline terms reported in Table 4 as well as in multivariate tables is HR = $e^{(\hat{b}_1)}$ for each unit increase in x up to $x = K$. Estimated HR for each unit increase in x for $x > K$ is HR = $e^{(\hat{b}_1 + \hat{b}_2)}$ (see Garg et al., 2012, for details). For the first spline term, the reported HR represents per each unit increase in risk below the knot. For the second spline term, the reported HR represents per each unit increase in risk above the knot (with a reference point at or above the knot). Equations are provided in Tables 5 and 7 to calculate HR (relative to unexposed) for PLI and PCLI above the knot. The reported p values for the second spline terms in Table 4 as well as multivariate tables are for a test of change in slope at the knot (i.e., test for $b_2 = 0$) in the linear spline transformed PH model. Thus, this p value does not correspond to the reported confidence intervals (CI) for second spline terms (i.e., 95% CI for HR = $e^{b_1} + e^{b_2}$) in Tables 4 through 8.

In Tables 5 through 8, an overall p value is provided for each variable in the multivariate model. This p value represents the significance of each variable in the final multivariate model with use of the likelihood ratio test. For spline transformed variables this p value is for the entire range of that variable (i.e., both spline terms).

Table 4 summarizes the results from unadjusted univariate analyses for relevant covariates for determining possible predictors of increased risk of LBP in multivariate models. The statistically significant ($p \leq .05$) factors were history of LBP, modified APGAR, Tense-Edge-Nervous, and housework. Maintenance work at home was

TABLE 3: Descriptive Statistics for Covariates and Job Physical Factors (N = 258)

Category	Variable	Categories	Mean ± Standard Deviation (Range) or %
Demographic	Age (years)	—	37.1 ± 12.0 (18.5–65.2)
	Gender	Male	67.1%
		Female	32.9%
Anthropometric	Body mass index (kg/m^2)	—	29.7 ± 7.5 (15.9–85.4)
Medical history	High blood pressure	Yes	14.3%
	High cholesterol	Yes	14.3%
	History of LBP[a]	Yes	25.2%
	LBP radiating to leg(s)	Yes	9.3%
	Sought health care	Yes	19.4%
	Modified duty	Yes	5.4%
	Lost time	Yes	5.4%
	Workers' compensation	Yes	2.7%
Psychosocial	APGAR composite[b]	—	4.7 ± 3.1 (0–13)
	Zung composite[b]	—	6.1 ± 3.7 (0–17)
	Tense-Edge-Nervous composite[c]	—	2.5 ± 1.9 (0–8)
Hobbies/activities participation[d]	Gardening	Yes	43.0%
	Housework	Yes	66.3%
	Maintenance	Yes	22.5%
	Snow shoveling	Yes	43.4%
	Swimming	Yes	8.5%
	Walking	Yes	60.0%
	Weights	Yes	25.2%
	Woodworking	Yes	10.5%
Job physical factors[e]	No. of task rotations	—	2.2 ± 1.9 (1–11)
	Second job	Yes	7.4%
	Peak subtask LI	Continuous (*M, SD*)	2.3 ± 1.1 (0.1–5.6)
		Continuous (median, interquartile range)	2.1 (1.5–3.1)
		LI ≤ 1.0	10.4%
		1.0 < LI ≤ 3.0	64.0%
		LI > 3.0	25.6%
	Peak task CLI	Continuous (*M, SD*)	2.8 ± 1.5 (0.1–8.5)
		Continuous (median, interquartile range)	2.4 (1.7–3.7)
		CLI ≤ 1.0	8.1%
		1.0 < CLI ≤ 3.0	55.4%
		CLI > 3.0	36.5%

Note. LBP = low-back pain; LI = lifting index; CLI = composite LI.
[a]LBP history includes (a) LBP radiating to leg(s), (b) sought health care for LBP, (c) modified duty for LBP, (d) lost time for LBP, and/or (e) received workers' compensation for LBP.
[b]APGAR and Zung are modified scales.
[c]Scale developed for this study.
[d]Aerobics, baseball, basketball, bicycling, football, motorcycling, remodeling, running, soccer, and tennis had less than 20% of workers participating, and none was statistically significant in univariate analyses ($p > .20$).
[e]Descriptive statistics are for first observation time period (baseline) only, and these statistics do not include changes in exposure during the follow-up period.

TABLE 4: Univariate Hazard Ratios (HR) for Peak Subtask Lifting Index (PLI), Peak Task Composite Lifting Index (PCLI), and Covariates (*N* = 258)

Category	Variable (Overall *p* Value)	Categories	*n* (Cases)	HR[a] [95% CI]	*p* Value
Demographic	Age (years) ($p = .13$)	Linear spline terms			
		Per year increase age ≤ 32.3	116 (62)	0.95[b] [0.90, 1.00]	.07
		Per year increase age > 32.3	142 (61)	1.05[b] [0.98, 1.13]	.15[c]
	Gender	Male	173 (82)	1.0	—
		Female	85 (41)	1.0 [0.69, 1.47]	0.96
Anthropometric	BMI (kg/m^2) ($p = .15$)	Linear spline terms			
		Per unit increase BMI ≤ 31.4	174 (93)	0.95[d] [0.91, 1.00]	.05
		Per unit increase BMI > 31.4	84 (30)	1.07[d] [1.00, 1.14]	.05[c]
Medical history	High blood pressure	No	221 (108)	1.0	—
		Yes	37 (15)	0.9 [0.52, 1.53]	.67
	High cholesterol	No	221 (103)	1.0	—
		Yes	37 (20)	1.1 [0.66, 1.73]	.78
	History of LBP[e]	No	193 (79)	1.0	—
		Yes	65 (44)	2.2 [1.5, 3.1]	<.001
	LBP radiating to leg(s)	No	234 (106)	1.0	—
		Yes	24 (17)	2.1 [1.24, 3.49]	.01
	Sought health care for LBP	No	208 (90)	1.0	—
		Yes	49 (33)	1.6 [1.05, 2.33]	.03
	Modified duty for LBP	No	244 (112)	1.0	—
		Yes	14 (11)	2.9 [1.54, 5.36]	<.01
	Lost time for LBP	No	244 (114)	1.0	—
		Yes	14 (9)	2.0 [1.03, 4.03]	.05
	Received workers' compensation for LBP	No	251 (120)	1.0	—
		Yes	7 (3)	1.0 [0.31, 3.09]	.97
Psychosocial	APGAR composite	Continuous	258 (123)	1.11 [1.05, 1.17]	<.001
	Zung composite	Continuous	258 (123)	1.03 [0.98, 1.08]	.30
	Tense-Edge-Nervous composite	Continuous	258 (123)	1.18 [1.07, 1.30]	<.001
Hobbies/ activities[f]	Gardening	No	147 (69)	1.0	—
		Yes	111 (54)	1.0 [0.70, 1.43]	.99
	Housework	No	87 (31)	1.0	—
		Yes	171 (92)	1.6 [1.10, 2.48]	.01
	Maintenance	No	200 (91)	1.0	—
		Yes	58 (32)	1.5 [0.99, 2.22]	.06
	Snow shoveling	No	146 (62)	1.0	—
		Yes	112 (61)	1.3 [0.88, 1.79]	.21
	Swimming	No	236 (110)	1.0	—
		Yes	22 (13)	1.7 [0.93, 2.93]	.11
	Walking	No	103 (48)	1.0	—
		Yes	155 (75)	0.9 [0.66, 1.36]	.76
	Weight lifting	No	193 (89)	1.0	—
		Yes	65 (34)	1.4 [0.91, 2.00]	.15
	Woodworking	No	235 (111)	1.0	—
		Yes	23 (12)	1.6 [0.88, 2.92]	.14

(continued)

TABLE 4: (continued)

Category	Variable (Overall *p* Value)	Categories	*n* (Cases)	HR[a] [95% CI]	*p* Value
Biomechanical stressors	PLI (NIOSH limits) (*p* = .02)	PLI ≤ 1.0	27 (9)[g]	1.0	—
		1.0 < PLI ≤ 3.0	165 (78)[g]	1.7 [0.85, 3.37]	0.14
		PLI > 3.0	66 (36)[g]	2.6 [1.22, 5.31]	0.01
	PLI (*p* = .05)	Linear spline terms			
		Per unit increase PLI ≤ 1.5	58 (25)[g]	2.17[h] [0.90, 5.28]	.09
		Per unit increase PLI > 1.5	200 (98)[g]	1.08[h] [0.88, 1.31]	.16[3]
	PCLI (NIOSH limits) (*p* = .07)	PCLI ≤ 1.0	21 (6)[g]	1.0	—
		1.0 < PCLI ≤ 3.0	143 (74)[g]	2.3 [1.02, 5.40]	.04
		PCLI > 3.0	94 (43)[g]	2.3 [0.96, 5.30]	.06
	PCLI (*p* = .02)	Linear spline terms			
		Per unit increase PCLI ≤ 2.0	90 (39)[g]	2.04[i] [1.17, 3.55]	.01
		Per unit increase PCLI > 2.0	168 (84)[g]	0.96[i] [0.83, 1.11]	.02[3]

Note. CI = confidence interval; BMI = body mass index; LBP = low-back pain; NIOSH = National Institute for Occupational Safety and Health.

[a]HR of 1.0 with no confidence interval indicates reference category for the variable.

[b]For age, $\hat{b}_1 = -0.0499$ and $\hat{b}_2 = 0.0523$. HR = $e^{b_1 \cdot age}$ and HR = $e^{b_1 \cdot age + b_2(age-32.3)}$ for age ≤ 32.3 and age > 32.3, respectively. HR per unit increase in age is e^{b1} for age ≤ 32.3 and $e^{b_1+b_2}$ for age > 32.3.

[c]This *p* value is for the second spline term and represents a test for change in slope at the knot (i.e., $b_2 = 0$). Thus, this *p* value *does not* correspond to the given confidence interval, which is for the HR (i.e., $e^{b_1+b_2}$) beyond the knot.

[d]For BMI, $\hat{b}_1 = -0.0481$ and $\hat{b}_2 = 0.0652$. HR = $e^{b_1 \cdot BM1}$ and HR = $e^{b_1 \cdot BM1 + b_2(BM1-31.4)}$ for BMI ≤ 31.4 and BMI > 31.4, respectively. HR per unit increase in BMI is e^{b_1} for BMI ≤ 31.4 and $e^{b_1+b_2}$ for BMI > 31.4.

[e]LBP history includes (a) LBP radiating to leg(s), (b) sought health care for LBP, (c) modified duty for LBP, (d) lost time for LBP, and/or (e) received workers' compensation for LBP.

[f]Aerobics, baseball, basketball, bicycling, football, motorcycling, remodeling, running, soccer, and tennis showed no statistically significant association with increased risk of any LBP (*p* > .20).

[g]For cases, *n* is based on exposure at the time a worker became a case. For noncases, *n* is based on exposure at baseline.

[h]For peak subtask PLI, $\hat{b}_1 = 0.7769$ and $\hat{b}_2 = -0.7034$. HR = $e^{b_1 \cdot PLI}$ and HR = $e^{b_1 \cdot PLI + b_2(PLI-1.5)}$ for PLI ≤ 1.5 and PLI > 1.5, respectively. HR per unit increase in PLI is e^{b_1} for PLI ≤ 1.5 and $e^{b_1+b_2}$ for PLI > 1.5.

[i]For peak task PCLI, $\hat{b}_1 = 0.7141$ and $\hat{b}_2 = -0.7569$. HR = $e^{b_1 \cdot CLI}$ and HR = $e^{b_1 \cdot PCLI + b_2(PCLI-2.0)}$ for PCLI ≤ 2.0 and PCLI > 2.0, respectively. HR per unit increase in PCLI is e^{b1} for PCLI ≤ 2.0 and $e^{b_1+b_2}$ for PCLI > 2.0.

marginally significant ($p \leq .06$). Age, BMI, swimming, weight lifting, and woodworking had $p \leq .20$.

Regarding univariate analyses of biomechanical measures of job physical exposures, when fitted with linear spline functions, both PLI and PCLI were statistically significant ($p = .05$ and $p = .02$, respectively; Table 4). PLI as a categorical variable according to limits prescribed by Waters et al. (2004) was statistically significant ($p = .02$). The PCLI as a categorical variable was marginally significant ($p = .07$; Table 4).

Multivariate Results

The multivariate PH regression model for covariates included age, gender, BMI, LBP history, APGAR, Tense-Edge-Nervous, and housework. When introduced into the multivariate model of

TABLE 5: Multivariate Model for Risk of Any Low-Back Pain (LBP) With the Peak Subtask Lifting Index (PLI) as Continuous Variable

Variable (Overall *p* Value)[a]	Category/Function	*n* (Cases)	HR	95% CI	*p* Value
PLI (*p* = .05)[a]	Spline terms				
	Per unit PLI ≤ 1.5	58 (25)[b]	2.57[c]	[1.00, 6.59]	.05
	Per unit PLI > 1.5	200 (98)[b]	1.01[c]	[0.81, 1.26]	.08[d]
	HR for PLI = 1.5		$2.57^{1.5} = 4.12$		
	HR for PLI > 1.5		$4.12*1.01^{(PLI-1.5)}$		
Covariates					
Age (years) (*p* = .38)[a]	Spline terms				
	Per unit age ≤ 32.3	116 (62)	0.96[e]	[0.90, 1.02]	.17
	Per unit age > 32.3	142 (61)	1.01[e]	[0.98, 1.03]	.20[d]
Gender (*p* = .76)[a]	Male	173 (82)	1.0	—	—
	Female	85 (41)	1.07	[0.70, 1.63]	.76
BMI (*p* = .61)[a]	Spline terms				
	Per unit BMI ≤ 31.4	174 (93)	0.98[f]	[0.93, 1.03]	.39
	Per unit BMI > 31.4	84 (30)	1.02[f]	[0.98, 1.05]	.31[d]
History of LBP (*p* < .001)[a]	No	193 (79)	1.0	—	—
	Yes	65 (44)	2.23	[1.44, 3.43]	<.001
APGAR composite (*p* = .02)[a]	Continuous per unit score	258 (123)	1.07	[1.01, 1.14]	.02
Tense-Edge-Nervous composite (*p* = .09)[a]	Continuous per unit score	258 (123)	1.10	[0.99, 1.22]	.08
Housework (*p* = .01)[a]	No	87 (31)	1.0	—	—
	Yes	171 (92)	1.71	[1.12, 2.62]	.01

Note. HR = hazard ratio; CI = confidence interval; BMI = body mass index.
[a]Overall significance associated with including each variable in the model using the likelihood ratio test.
[b]For cases, *n* is based on exposure at the time a worker became a case. For noncases, *n* is based on exposure at baseline.
[c]For peak subtask PLI, $\hat{b}_1 = 0.9434$ and $\hat{b}_2 = -0.9333$. HR = $e^{b_1 \cdot LI}$ and HR = $e^{b_1 \cdot PLI + b_2 (PLI-1.5)}$ for score ≤ 1.5 and score > 1.5, respectively. HR per unit increase in PLI is e^{b_1} for PLI ≤ 1.5 and $e^{b_1+b_2}$ for PLI > 1.5.
[d]This *p* value is for the second spline term and represents a test for change in slope at the knot (i.e., $b_2 = 0$). Thus, this *p* value *does not* correspond to the given confidence interval, which is for the HR (i.e., $e^{b_1+b_2}$) beyond the knot.
[e]For age, $\hat{b}_1 = -0.0423$ and $\hat{b}_2 = 0.0505$. HR = $e^{b_1 \cdot age}$ and HR = $e^{b_1 \cdot age + b_2 (age-32.3)}$ for age ≤ 32.3 and age > 32.3, respectively. HR per unit increase in age is e^{b_1} for age ≤ 32.3 and $e^{b_1+b_2}$ for age > 32.3.
[f]For BMI, $\hat{b}_1 = -0.0252$ and $\hat{b}_2 = 0.0331$. HR = $e^{b_1 \cdot BMI}$ and HR = $e^{b_1 \cdot BMI + b_2 (BMI-31.4)}$ for BMI ≤ 31.4 and BMI > 31.4, respectively. HR per unit increase in BMI is e^{b_1} for BMI ≤ 31.4 and $e^{b_1+b_2}$ for BMI > 31.4.

covariates, PLI—treated as a continuous variable with use of a linear spline function—showed a statistically significant trend for increased risk of LBP (*p* = .05; Table 5). The linear spline function showed that risk (HR) increased first at a faster rate up to PLI ≤ 1.5 (HR = 2.6 per unit increase, 95% CI [1.00, 6.59]) and then rose at a much slower rate for PLI > 1.5 (Table 5). The HR relative to unexposed for PLI > 1.5 is calculated as $4.12*1.01^{(PLI-1.5)}$, where 4.12 is the HR at PLI = 1.5 (knot) and 1.01 is the HR per unit increase in PLI above the knot (with respect to a reference point at or above the knot). As a categorical variable according to the limits prescribed by Waters et al. (1994), PLI showed a statistically significant trend (*p* = .03, HR = 1.9 for 1.0 < PLI ≤ 3.0 and HR = 2.6 for PLI > 3.0; Table 6).

When the PCLI was introduced into the multivariate model of covariates and treated as a continuous variable with use of a linear spline

TABLE 6: Multivariate Model for Risk of Any Low-Back Pain (LBP) With the Peak Subtask LI (PLI) as Categorical Variable Using the NIOSH Recommended Limits

Variable (Overall *p* Value)[a]	Category/Function	*n* (Cases)	HR	95% CI	*p* Value
PLI (p = .03)[a]	PLI ≤ 1.0	27 (9)[b]	1.0		
	1.0 < PLI ≤ 3.0	165 (78)[b]	1.89	[0.93, 3.85]	.08
	PLI > 3.0	66 (36)[b]	2.55	[1.19, 5.46]	.02
Covariates					
Age (years) (p = .38)[a]	Spline terms				
	Per unit age ≤ 32.3	116 (62)	0.96[c]	[0.90, 1.02]	.16
	Per unit age > 32.3	142 (61)	1.06[c]	[0.98, 1.14]	.18[d]
Gender (p = .45)[a]	Male	173 (82)	1.0	—	—
	Female	85 (41)	1.18	[0.77, 1.80]	.45
BMI (p = .74)[a]	Spline terms				
	Per unit BMI ≤ 31.4	174 (93)	0.98[e]	[0.94, 1.04]	.53
	Per unit BMI > 31.4	84 (30)	1.03[e]	[0.96, 1.10]	.43[4]
History of LBP (p < .001)[a]	No	193 (79)	1.0	—	—
	Yes	65 (44)	2.17	[1.41, 3.33]	<.001
APGAR composite (p = .02)[a]	Continuous per unit score	258 (123)	1.08	[1.01, 1.14]	.02
Tense-Edge-Nervous composite (p = .08)[a]	Continuous per unit score	258 (123)	1.10	[0.99, 1.22]	.08
Housework (p = .01)[a]	No	87 (31)	1.0	—	—
	Yes	171 (92)	1.69	[1.10, 2.58]	.02

Note. NIOSH = National Institute for Occupational Safety and Health; HR = hazard ratio; CI = confidence interval; BMI = body mass index.
[a]Overall significance associated with including each variable in the model using the likelihood ratio test.
[b]For cases, *n* is based on exposure at the time a worker became a case. For noncases, *n* is based on exposure at baseline.
[c]For age, $\hat{b}_1 = -0.0432$ and $\hat{b}_2 = 0.0536$. HR = $e^{b_1 \cdot age}$ and HR = $e^{b_1 \cdot age + b_2(age-32.3)}$ for age ≤ 32.3 and age > 32.3, respectively. HR per unit increase in age is e^{b_1} for age ≤ 32.3 and $e^{b_1+b_2}$ for age > 32.3.
[d]This *p* value is for the second spline term and represents a test for change in slope at the knot (i.e., $b_2 = 0$). Thus, this *p* value *does not* correspond to the given confidence interval, which is for the HR (i.e., $e^{b_1+b_2}$) beyond the knot.
[e]For BMI, $\hat{b}_1 = -0.0164$ and $\hat{b}_2 = 0.0284$. HR = $e^{b_1 \cdot BMI}$ and HR = $e^{b_1 \cdot BMI + b_2(BMI-31.4)}$ for BMI ≤ 31.4 and BMI > 31.4, respectively. HR per unit increase in BMI is e^{b_1} for BMI ≤ 31.4 and $e^{b_1+b_2}$ for BMI > 31.4.

function, it showed a statistically significant association with increased risk of LBP (p = .02). The multivariate model showed that the risk for LBP increased with an increase in PCLI up to ≤ 2.0 (HR = 2.1 per unit increase, 95% CI [1.16, 3.63], p = .01). With a further increase in PCLI (>2), there was evidence that risk remained elevated, although it began to decrease slightly (Table 7). The HR relative to unexposed for PCLI > 2.0 is calculated as $4.22 * 0.97^{(PCLI-2.0)}$, where 4.22 is the HR at PCLI = 2.0 (knot) and 0.97 is the HR per unit increase in PCLI above the knot (with respect to a reference point at or above the knot). In the multivariate model, PCLI treated as a categorical variable was statistically significantly associated with increased risk of LBP (p = .05). The HRs for 1.0 > PCLI ≤ 3.0 and PCLI > 3.0 were about the same (2.6 and 2.3; Table 8).

Estimated risk of LBP (i.e., HR) for different levels of physical exposure was calculated as HR = $e^{\hat{b}_1 x + \hat{b}_2 (x-K)_+}$. In the multivariate analyses, $\hat{b}_1$ and $\hat{b}_2$ were 0.943 and −0.933, respectively, for PLI spline terms (note 3 of Table 5) and 0.720 and −0.755, respectively, for the PCLI spline terms (footnote 3 of Table 7). These HRs are

TABLE 7: Multivariate Model for Risk of Any Low-Back Pain (LBP) With Peak Task Composite Lifting Index (PCLI) as Continuous Variable

Variable (Overall *p* Value)[1]	Category/Function	*n* (Cases)	HR	95% CI	*p* Value
PCLI (p = .02)[a]	Spline terms				
	Per unit PCLI ≤ 2.0	90 (39)[b]	2.05[c]	[1.16, 3.63]	.01
	Per unit PCLI > 2.0	168 (84)[b]	0.97[c]	[0.82, 1.13]	.02[d]
	HR for PCLI = 2.0		$2.05^{2.0} = 4.22$		
	HR for PCLI > 2.0		$4.22 * 0.97^{(PCLI-2.0)}$		
Covariates					
Age (years) (p = .48)[a]	Spline terms				
	Per unit age ≤ 32.3	116 (62)	0.96[e]	[0.91, 1.02]	.22
	Per unit age > 32.3	142 (61)	1.01[e]	[0.98, 1.03]	.25[d]
Gender (p = .64)[a]	Male	173 (82)	1.0	—	—
	Female	85 (41)	1.08	[0.71, 1.62]	.73
BMI (p = .73)[a]	Spline terms				
	Per unit BMI ≤ 31.4	174 (93)	0.98[f]	[0.93, 1.03]	.37
	Per unit BMI > 31.4	84 (30)	1.02[f]	[0.98, 1.05]	.29[d]
History of LBP (p < .001)[a]	No	193 (79)	1.0	—	—
	Yes	65 (44)	2.22	[1.44, 3.42]	<.001
APGAR composite (p = .02)[a]	Continuous per unit score	258 (123)	1.07	[1.01, 1.14]	.02
Tense-Edge-Nervous composite (p = .07)[a]	Continuous per unit score	258 (123)	1.10	[0.99, 1.22]	.07
Housework (p = .01)[a]	No	87 (31)	1.0	—	—
	Yes	171 (92)	1.69	[1.10, 2.60]	.02

Note. HR = hazard ratio; CI = confidence interval; BMI = body mass index.
[a]Overall significance associated with including each variable in the model using the likelihood ratio test.
[b]For cases, *n* is based on exposure at the time a worker became a case. For noncases, *n* is based on exposure at baseline.
[c]For peak task CLI, $\hat{b}_1 = 0.7200$ and $\hat{b}_2 = -0.7554$. HR = $e^{b_1 \cdot PCLI}$ and HR = $e^{b_1 \cdot PCLI + b_2 (PCLI-2.0)}$ for score ≤ 2.0 and > 2.0 respectively. HR per unit increase in PCLI is e^{b_1} for PCLI ≤ 2.0 and $e^{b_1+b_2}$ for PCLI > 2.0.
[d]This *p* value is for the second spline term and represents a test for change in slope at the knot (i.e., $b_2 = 0$). Thus, this *p* value *does not* correspond to the given confidence interval, which is for the HR (i.e., $e^{b_1+b_2}$) beyond the knot.
[e]For age, $\hat{b}_1 = -0.0375$ and $\hat{b}_2 = 0.0452$. HR = $e^{b_1 \cdot age}$ and HR = $e^{b_1 \cdot age + b_2 (age-32.3)}$ for age ≤ 32.3 and age > 32.3, respectively. HR per unit increase in age is e^{b_1} for age ≤ 32.3 and $e^{b_1+b_2}$ for age > 32.3.
[f]For BMI, $\hat{b}_1 = -0.0230$ and $\hat{b}_2 = 0.0381$. HR = $e^{b_1 \cdot BMI}$ and HR = $e^{b_1 \cdot BMI + b_2 (BMI-31.4)}$ for BMI ≤ 31.4 and BMI > 31.4, respectively. HR per unit increase in BMI is e^{b_1} for BMI ≤ 31.4 and $e^{b_1+b_2}$ for BMI > 31.4.

summarized in Table 9 for different levels of PLI and PCLI. Estimated peak HR for PLI was 4.3 at PLI = 6.0. Similarly, the estimated peak HR for PCLI was 4.2 at PCLI = 2.0 (Table 9). Workers exposed to biomechanical stressors with PLI or PCLI > 1.0 had at least 2 times the risk of developing LBP as compared WITH those unexposed ($p \leq .05$; Table 9). Those workers exposed to work PLI or PCLI > 3.0 had at least 3.5 times the risk of developing LBP as compared with those unexposed.

DISCUSSION

The results of this prospective cohort study of manufacturing workers suggest that LBP has a complex, multifactorial etiology. These factors include (a) job physical factors, (b) past history of LBP, (c) psychosocial factors (low work

TABLE 8 : Multivariate Model for Risk of Any Low-Back Pain (LBP) With Peak Task Composite Lifting Index (PCLI) as Categorical Variable Using the NIOSH Recommended Limits

Variable (Overall *p* Value)[a]	Category/Function	*n* (Cases)	HR	95% CI	*p* Value
PCLI (p = .05)[a]	PCLI ≤ 1.0	21 (6)[b]	1.0		
	1.0 < PCLI ≤ 3.0	143 (74)[b]	2.56	[1.10, 5.98]	.03
	PCLI > 3.0	94 (43)[b]	2.31	[0.97, 5.50]	.06
Covariates					
Age (years) (p = .35)[a]	Spline terms				
	Per unit age ≤ 32.3	116 (62)	0.96[c]	[0.90, 1.02]	.16
	Per unit age > 32.3	142 (61)	1.05[c]	[0.97, 1.14]	.20[d]
Gender (p = .94)[a]	Male	173 (82)	1.0	—	—
	Female	85 (41)	1.02	[0.67, 1.54]	.94
BMI (p = .54)[a]	Spline terms				
	per unit BMI ≤ 31.4	174 (93)	0.98[e]	[0.93, 1.03]	.34
	per unit BMI > 31.4	84 (30)	1.04[e]	[0.97, 1.12]	.25[d]
History of LBP (p < .01)[a]	No	193 (79)	1.0	—	—
	Yes	65 (44)	2.10	[1.37, 3.23]	<.001
APGAR composite (p = .02)[a]	Continuous per unit score	258 (123)	1.08	[1.01, 1.15]	.01
Tense-Edge-Nervous Composite (p = .06)[a]	Continuous per unit score	258 (123)	1.10	[1.00, 1.22]	.06
Housework (p < .01)[a]	No	87 (31)	1.0	—	—
	Yes	171 (92)	1.73	[1.13, 2.64]	.01

Note. NIOSH = National Institute for Occupational Safety and Health; HR = hazard ratio; CI = confidence interval; BMI = body mass index.
[a]Overall significance associated with including each variable in the model using the likelihood ratio test.
[b]For cases, *n* is based on exposure at the time a worker became a case. For noncases, *n* is based on exposure at baseline.
[c]For age, $\hat{b}_1 = -0.0432$ and $\hat{b}_2 = 0.0499$. HR = $e^{b_1 \cdot age}$ and HR = $e^{b_1 \cdot age + b_2(age-32.3)}$ for age ≤ 32.3 and age > 32.3, respectively. HR per unit increase in age is e^{b_1} for age ≤ 32.3 and $e^{b_1+b_2}$ for age > 32.3.
[d]This *p* value is for the second spline term and represents a test for change in slope at the knot (i.e., b_2 = 0). Thus, this *p* value *does not* correspond to the given confidence interval, which is for the HR (i.e., $e^{b_1+b_2}$) beyond the knot.
[e]For BMI, $\hat{b}_1 = -0.0244$ and $\hat{b}_2 = 0.0411$. HR = $e^{b_1 \cdot BMI}$ and HR = $e^{b_1 \cdot BMI + b_2(BMI-31.4)}$ for BMI ≤ 31.4 and BMI > 31.4, respectively. HR per unit increase in BMI is e^{b_1} for BMI ≤ 31.4 and $e^{b_1+b_2}$ for BMI > 31.4.

support [modified APGAR] and feeling tense, on edge, or nervous [Tense-Edge-Nervous]), and (d) activities outside of work (housework). Regarding job physical factors, both the PLI and PCLI predicted risk of LBP when treated both as categorical variables and as continuous variables. In their continuous forms, PLI and PCLI predicted risk of LBP with a maximum HR of 4.3 at 4.2, respectively (Table 9).

LBP Case Definition

In theory, cohort studies examining risk factors for occurrence of a disease require that the subjects should be free of the disease at enrollment. Because LBP is common and episodic, it is appropriate to study workers who are free of LBP for a specific period of time and can thus be considered at risk for a new episode of LBP. In this study, workers were eligible to become a new case for LBP if they were pain free at baseline for at least 90 days. This eligibility requirement is consistent with the past studies that have used a pain-free period of 1 to 3 months at baseline to define a new episode of LBP (Harkness et al., 2003; Hoogendoorn, Bongers, de Vet, Ariens, 2002; Norman et al., 1998).

TABLE 9: Hazard Ratio Estimates for Peak Subtask Lifting Index (PLI) and Peak Task Composite LI (PCLI) Based on Multivariate Analyses

PLI	Hazard Ratio[a]	PCLI	Hazard Ratio[a]
0.2	1.2	0.2	1.2
0.4	1.5	0.4	1.4
0.6	1.8	0.6	1.6
0.8	2.1	0.8	1.8
1.0	2.6	1.0	2.1
1.5[b]	4.1	1.5	2.9
2.0	4.1	2.0[b]	4.2
2.5	4.2	2.5	4.1
3.0	4.2	3.0	4.1
3.5	4.2	3.5	4.0
4.0	4.2	4.0	3.9
4.5	4.2	4.5	3.9
5.0	4.3	5.0	3.8
6.0	4.3	6.0	3.7

[a]Hazard ratio estimates are from results in Tables 5 and 7 and were calculated using the equation $e^{\hat{b}_1 x+\hat{b}_2 (x-K)+}$.
[b]Value represents the knot for the linear spline function.

We defined an LBP case as pain in lower back of any intensity lasting ≥1 day, consistent with de Vet et al. (2002). Use of this case definition (a) reduced the number of incident-eligible workers (256 workers were baseline prevalent), (b) likely resulted in the relatively high incident rate (39.5 per 100 person-years) reported in this study, and (c) may have attenuated the exposure response relationships, as LBP is common in the general population. There is some evidence to suggest that risk factors vary with case definitions of LBP (Ozguler, Leclerc, Landre, Pietri-Taleb, & Niedhammer, 2000). This variation might explain the inconsistent results reported among studies of LBP.

Job Physical Factors

PLI is a measure of biomechanical stressors to low back from lifting and lowering of loads from a subtask, and the PCLI is an estimate of stressors from the entire task. In this study, we found that both PLI and PCLI were associated with increased risk of LBP ($p \leq .05$). Surprisingly, predictions from PLI and PCLI for increased risk of LBP were fairly comparable (Table 9). Authors of a few studies have examined relationships between the LI and risk of LBP (Boda et al., 2012; Marras et al., 1999; Waters et al., 1999, 2011) mostly by categorizing LI into low, medium, and high risk. These researchers have all reported an association between LI and prevalence or incidence of LBP. This study adds to a growing body of evidence that the RNLE is a useful tool for estimating exposure to low-back biomechanical stressors.

As stated in the Method section, we capped RNLE multipliers at their maximum penalties in those situations in which physical measurements exceeded Waters et al.'s (1994) recommended limits. RNLE limits on multipliers were provided as design limits. Strict adherence to those limits would have resulted in some LIs and CLIs having infinite values, thus making statistical analyses impossible.

We used "peak exposure" to assign job physical exposure to the workers. Prior studies have shown that peak job physical demands are better predictors of LBP than average or "typical" job physical demands (Boda et al., 2012; Herrin et al., 1986; Marras et al., 1993). It is possible that had we used average, time-weighted-average, or typical exposure to assign physical exposure to the workers, the associations would not have been as strong.

An important issue in epidemiological studies is the selection of method used to assess job physical factors (Burdorf, 2010; Coenen et al., 2012). Many of the past studies have involved use of self-reports, observer subjective estimates, or an aggregate assignment of job exposure to a group of workers (group analysis) to estimate job physical demands. Self-reported exposures, although used in many epidemiological studies, are prone to measurement error and recall biases (Balogh et al., 2004; Punnett & Wegman, 2004). Observer subjective estimates of job physical factors, although frequently used, have lower validity than direct measurement of the job (Spielholz, Silverstein, Morgan, Checkoway, & Kaufman, 2001; Takala et al., 2010). Furthermore, Coenen et al. (2012) suggested that it is difficult to estimate stresses to low back from visual observation of a job. Group analysis does not account for individual differences in physical exposure when multiple workers perform similar jobs; however, Jansen and Burdorf (2003) found that the same physical exposure assigned to a group of workers (group approach) showed higher association with LBP than did the measurement on each individual worker.

In this study, biomechanical stressors were carefully measured for each individual worker. It may be because of these individualized measurements of biomechanical stressors that we found stronger associations than in prior investigations.

Individual Factors

In this study, we did not find statistically significant associations between LBP and gender, age, or BMI. In general, authors of prior epidemiological investigations have reported that females are at a modest increased risk for LBP; however, results are inconsistent (Deyo & Tsui-Wu, 1987; Manchikanti, 2000; Walker et al., 2004). In this study, age was marginally significant in univariate analysis but was not statistically significant in multivariate analysis. The nonsignificant age effect was *U* shaped, with risk decreasing until age 32 and then increasing. Obesity is generally considered to be a risk factor for LBP; however, systematic reviews have revealed only weak associations between body weight and LBP (Leboeuf-Yde, 2000; Shiri et al., 2009). Furthermore, Shiri et al. (2009) noted that obesity is more likely in those individuals who are sedentary during work or leisure activities. Workers in this study were exclusively employed in manual materials handling jobs and had a high level of participation in hobbies and physical activities outside of work. It is possible that high BMI reported in this study may reflect higher muscle mass rather than adipose tissue.

We found that history of LBP was strongly associated with increased risk of developing LBP. This finding is consistent with evidence in the literature that history of LBP is associated with future LBP (Hincapie et al., 2008; Matsudaira et al., 2012; Nelson & Hughes, 2009; Tubach et al., 2002). Different researchers have used different definitions to define history of LBP, such as prior LBP, LBP injury at work, sick leave due to LBP, LBP with lost time, workers' compensation received due to LBP, and so on. We defined LBP history as LBP that resulted in workers' compensation, lost time, light duty, visit to a health care provider, and/or LBP radiating to the leg(s). Most individual measures of prior LBP in this study (Table 4) showed statistically significant association with LBP in univariate analyses.

We found that low coworker and supervisor support at work (modified APGAR) and feeling tense, on edge, or nervous (Tense-Edge-Nervous) were associated with increased risk of LBP. Authors of past studies have found inconsistent associations between psychosocial factors and LBP. Although several researchers have reported an association between low social support at work or low job satisfaction and LBP (Hoogendoorn, van Popel, et al., 2000; Macfarlane et al., 2009; Matsudaira et al., 2012; Papageorgiou et al., 1997; Tubach et al., 2002; Van Nieuwenhuyse et al., 2004), others have found either no association or weak association (Clays et al., 2007; Hartvigsen, Lings, Leboeuf-Yde, & Bakketeig, 2004; Hincapie et al., 2008; Hoogendoorn, Bongers, de Vet, Twisk, et al., 2002; Jansen et al., 2004; Ramond et al., 2011). Davis and Heaney (2000) reported that this inconsistency in past studies may be due to (a) lack of controlling for potential confounding from biomechanical stressors at work and (b) differences in measures of psychosocial and biomechanical stressors used in these studies.

The Tense-Edge-Nervous Scale was developed for use in this study to measure anxiety. There is little information available on association between increased anxiety and risk of LBP. Our results are consistent with a previous report that tension, anxiety, and nervousness are associated with increased risk of LBP (Bongers, De Winter, Kompier, & Hildebrandt, 1993). On the basis of laboratory experiments, Marras, Davis, Heaney, Maronitis, and Allread (2000) concluded that psychosocial stressful environment might make people with certain personality traits more susceptible to an increase in spine loading and low-back disorder risk. The role of anxiety in future risk of LBP needs further investigation.

We did not find statistical evidence that hobbies and physical activities outside of work, other than housework, were associated with increased risk of LBP. The observed association between housework and LBP found in this study needs further investigation. Authors of a recent study reported a moderate risk of chronic LBP for those who had a sedentary lifestyle (odds ratio [OR] = 1.31) as well as for those who were involved in strenuous activities (OR = 1.22) (Heneweer, Vanhees, & Picavet, 2009). Our findings are consistent with those of two systematic literature reviews that showed no evidence for association between LBP and standing, sitting, walking, sports, or leisure-time physical activities (Bakker et al., 2009; Hoogendoorn, van Popel, Bongers, Koes, & Bouter, 1999).

Strengths and Weaknesses of the Study

This study's strengths include (a) prospective methods, (b) enrollment of a large number of workers from diverse employers performing different work, (c) assessments and measurements of numerous potential covariates, (d) use of computerized structured interviews, (e) detailed quantification of each worker's job physical factors, (f) blinding of team members, (g) monthly health status follow-ups, (h) quarterly job physical exposure assessments, and (i) cohort follow-up of up to 4.5 years. This study's detailed analyses of biomechanical stressors for each worker likely minimized exposure misclassifications and provided more accurate exposure assessments for individual workers. Collectively, these methods, particularly, detailed quantification of job physical exposures, appear likely to have resulted in stronger measures of effect than in many prior studies, including evidence of an exposure-response relationship between job physical factors and LBP.

Limitations include that workers were primarily from manufacturing environments; thus the results might not be directly applicable in other environments, particularly to office settings. Furthermore, within these manufacturing environments, the effect of facility or industry could not be evaluated due to small sample size (123 LBP cases and 30 facilities). The 72% participation rate among those workers attending meetings and estimated >50% rate from all potentially eligible workers could be a source of bias if those who did not participate differed substantially from those who did. Certain hobbies and physical activities, such as gardening and snow shoveling, are seasonal and therefore time dependent but were treated as time independent in this study due to data limitations. Use of psychosocial questions developed for use in this study might have resulted in misclassification of those potential risk factors.

CONCLUSIONS

LBP in manufacturing settings appears to have a multifactorial etiology. Factors include job physical exposure (PLI and PCLI), LBP history, physical activities outside of work (housework), and psychosocial factors (modified APGAR and Tense-Edge-Nervous). Both the PLI and PCLI showed a statistically significant exposure-response relationship for risk of LBP ($p \leq .04$). This study supports the findings from previous studies that biomechanical stressors from job physical exposure play a role in the development of LBP in manufacturing environments. The PLI and PCLI are useful metrics for estimating exposure to biomechanical stressors. These findings suggest that jobs should be designed to keep both PLI and PCLI as low as possible to reduce the risk of LBP.

APPENDIX

Modified Zung Depression Scale and Tense-Edge-Nervous Scale Used to Assess Psychosocial Factors in This Study

TABLE A1: Modified Zung Depression Index

Item	Rarely or none of the time (less than 1 day per week)	Some or little of the time (1–2 days per week)	A moderate amount of time (3–4 times per week)	Most of the time (5–7 days per week)
1. I feel downhearted and sad.				
2. I feel that nobody cares.				
3. I get tired for no reason.				
4. I feel that I am useful and needed.				
5. I am still able to enjoy those things I used to.				
6. I eat as much as I used to.				
7. I am more irritable than usual.				
8. I feel hopeful about the future.				

TABLE A2: Tense-Edge-Nervous Scale

Item	Never	Sometimes	Often	Always
1. How often during the past month have you felt "on edge"?				
2. How often during the last month have you felt tense?				
3. How often during the past month have you felt nervous or anxious?				

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KEY POINTS

- Low-back pain has a multifactorial etiology.
- Risk factors for low-back pain include biomechanical stressors, low-back pain history, psychosocial factors, and housework.
- Peak job demands are associated with increased risk of low-back pain.
- Lifting index and composite lifting index are useful metrics for estimating exposure to biomechanical stressors.
- Jobs should be designed to keep lifting index and composite lifting index low to reduce low-back pain in workplaces.

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