FINAL PROGRESS REPORT

Grant Number: R01OH010916

Sponsor: National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention

Title: Exposure Response Relationships for Low Back Pain from Pooled Data

Project start and end dates: 9/1/15 – 8/31/20

Program Director / Principal Investigator: Jay Kapellusch, PhD

Co-Investigators: Kurt T. Hegmann, MD, Matthew S. Thiese, PhD, and Andrew S. Merryweather, PhD (Rocky Mountain Center for Occupational and Environmental Health, University of Utah); William S. Marras, PhD and Sue A. Ferguson, PhD (The Ohio State University), Ming-Lun Lu, PhD (NIOSH), and Elizabeth Malloy, PhD (American University)

Applicant Organization:
University of Wisconsin – Milwaukee
Office of Sponsored Programs
P.O. Box 340
Milwaukee, WI
414-229-5337 / grant-notice@uwm.edu

Date of completion of Final Report: November 30, 2020

Table of Contents

List of Terms and Abbreviations

RNLE	Revised NIOSH Lifting Equation
AU	American University
BMI	Body Mass Index
CI	Confidence Interval
CLI	Composite Lifting Index
CULI	Cumulative Lifting Index
FILI	Frequency Independent Lifting Index
HR	Hazard Ratio
HWSE	Healthy Worker Survivor Effect
LBP	Low Back Pain
LBP Hx	Lifetime History of LBP
LT-LBP	Lost Time due to Low Back Pain
MSD	Musculoskeletal Disorder
NIOSH	The National Institute for Occupational Safety and Health
OR	Odds Ratio
OSU	The Ohio State University
pkCLI	Peak Composite Lifting Index
pkFILI	Peak Frequency Independent Lifting Index
PR	Prevalence Ratio
P-Y	Person-Years
SC-LBP	Seeking Care for Low Back Pain
SSW	Self-Selection of Workers
TWA	Time Weighted Average
UU	University of Utah
UWM	University of Wisconsin – Milwaukee

Abstract

Low Back Pain (LBP), and related outcomes are burdensome occupational MSDs for workers and employers. Prior studies have examined risk factors but only limited information is available about quantified exposure-response relationships for LBP and its related outcomes of seeking care for LBP (SC-LBP) and lost time due to LBP (LT-LBP). There is scientific disagreement about whether or not biomechanical exposures are independent risk factors for LBP.

Previously collected data were pooled from three research sites. Workers from 82 facilities representing 21 predominantly manufacturing and warehousing industries in six US states were included. Demographic, psychosocial, and health outcomes data were collected on each worker. Workers were followed for up to 4.5 years. Occupational physical exposures were measured for each task performed by each worker.

A total of 1,976 workers provided data. Complete data were available and successfully pooled for 1,650 (83.5%). Many workers (395) performed multi-task jobs (i.e., job-rotation). A large majority of the cohort was male (75%) and white (68%). Mean age was 35.5±11.3 years, and mean BMI was 28.0±6.0. Lift/Lower activities were quantified using the Revised NIOSH Lifting Equation (RNLE) with summary measures at the sub-task, task, and job levels. Sub-tasks were individual lifts/lowers (quantified with peak RNLE Frequency Independent Lifting Index), tasks were collections of sub-tasks performed as a set (quantified with the peak RNLE Composite Lifting Index), and jobs were collections of tasks performed in a workday (quantified with the RNLE Cumulative Lifting Index). Independent lifting parameters such as peak weight, peak reach and peak twisting were also analyzed.

Exposure-response relationships were developed for prevalence of LBP outcomes using logistic regression and developed for incidence of LBP outcomes using proportional hazards regression. Continuous analyses were performed with linear splines used to account for non-linear exposure-response.

The RNLE was consistently associated with prevalence and incidence of LBP, SC-LBP, and LT-LBP at the peak sub-task, peak task, and job-levels. Peak task exposure was most strongly associated with prevalence and peak sub-task most strongly associated with incidence. In addition, peak reaching and peak twisting were consistently and strongly associated with incidence of all three LBP outcomes.

Increased age was associated with prevalence of LBP but not SC-LBP or LT-LBP. Conversely, increased age was protective for incidence of LBP. Gender and BMI were not associated. Psychosocial factors such as coworker support and job satisfaction were associated with prevalence of all three outcomes but not incidence. Lifetime history of LBP was associated with prevalence and incidence of outcomes. In prevalence analyses LBP history appeared to confound the effects of physical exposure and reduced the ORs of the RNLE measures by 40 to 50%.

Overall, evidence is provided that biomechanical exposures are independent risk factors for LBP and related outcomes. The findings of this study should help inform future LBP research and intervention strategies. Continuous exposure-response relationships provide a basis for companies to develop exposure policies. The RNLE provides a foundation for detailed job design, evaluation, and decision making. Associations with individual parameters of lifts/lowers provide a basis for simple surveillance strategies.

Section 1: Final Progress Report

1.1 Significant-Key Findings

This study found consistent and strong evidence that biomechanical factors both measured using the Revised NIOSH Lifting Equation (RNLE) and measured as independent parameters were associated with prevalence and incidence of low back pain (LBP) and related outcomes after adjusting for worker individual and psychosocial factors.

RNLE measures at the sub-task-level (i.e., individual lift/lower), task-level (i.e., collection of lifts/lowers performed as a set), and job-level (i.e., multi-tasks with job rotation) were associated with both prevalence of incidence of the outcomes of: (i) any Low Back Pain (LBP) lasting seven or more consecutive days, (ii) seeking care for LBP (SC-LBP), and (iii) lost-time due to LBP (LT-LBP). Peak task-level exposure was most strongly associated with prevalence of outcomes whereas peak sub-task-level exposure was most strongly associated with incidence of outcomes. Job-level exposure was also strongly associated with incidence. RNLE associations were not altered by the presence of age, gender, BMI or psychosocial factors. Prior history of LBP lasting four or more weeks weakened the magnitude of RNLE associations with prevalence of LBP outcomes but had no effect on incidence. On average, workers exposed to the NIOSH suggested “high” exposure level of RNLE=3.0 were at between 60% to 240% increased risk of prevalent LBP outcomes and at between 30% to 70% increased risk for incidence of LBP outcomes as compared to those at the NIOSH suggested “low” exposure level of RNLE=1.0.

Peak lift/lower parameters such as peak weight lifted, peak reach, and peak trunk twist were strongly associated with incidence of all three LBP outcomes and these associations were not affected by age, gender, BMI, or prior history of LBP. This finding, combined with those of the RNLE measures provide strong evidence that biomechanical factors are independent risk factors for LBP and related outcomes; and refutes the findings of recent systematic reviews that have suggested that biomechanical factors are not independent risk factors for LBP.

Poor supervisor support and poor job satisfaction were associated with prevalence of LBP outcomes after adjusting for physical exposure, and age, gender, BMI, and history of LBP. Other psychosocial factors such as control over breaks and control over task order also showed association with prevalence of LBP outcomes. Psychosocial factors did not show association with incidence of LBP, perhaps due to exclusion of prevalent workers or because psychosocial factors were measured only at baseline and thus unable to account for any changes over time.

History of LBP was a consistent and strong risk factor for future LBP and related outcomes. History of LBP was also a confounder of physical exposure among prevalent workers where it reduced magnitude of associations with LBP outcomes by up to 50% and worsened statistical association as well. The persistent and consistently strong effect of prior LBP demonstrates the importance of preventing or substantially delaying the first onset of substantial LBP.

1.2 Translation of Findings

We provide continuous exposure-response relationships between lifting/lowering physical exposure and incidence of LBP, SC-LBP, and LT-LBP. Companies and governmental agencies can use these relationships to develop physical exposure policies and/or regulations. The measures rely on the widely used and freely available RNLE and because measures were analyzed for subtasks and for whole jobs can be translated into to both simple surveillance and job design strategies.

From a health and safety surveillance perspective the findings that simple measures such as peak weight, peak reach, and peak twist are strong predictors of LBP outcomes should be

welcome. These parameters are easy to quantify and monitor. Further, regular monitoring in a given industry would create internal data that could be used to implement company-wide policies such as product or process weight limits or altered workstation designs that prevent over-exposure to heavy lifting, twisting or reaching. Similarly, the finding that peak sub-task-level RNLE analyses are as or more effective than complex job-level RNLE analyses could dramatically simplify what is needed for semi-comprehensive surveillance of complex working environments while still taking advantage of key aspects of the RNLE such as the ability to integrate the effects of multiple parameters and provide a list of jobs/tasks for prioritized attention.

From a job design standpoint, validation of the RNLE and in particular its measures at the sub-task-, task-, and job-levels should lead to improved use in engineering-based job design and intervention strategies. The RNLE has proven flexible and provides stable and consistent measures of exposure that are directly and predictably related to one another. These attributes are critical for any engineering or design tool to be used over long periods and especially in any industry that relies on a continuous improvement approach where small improvements are made over time. The continuous exposure-response relationships provided from this study should aid those who want to use the RNLE in these engineering driven environments.

Lastly the RNLE is freely available and though it does require some training to use properly, the tool is not inherently difficult to understand and does not require intense knowledge of biomechanics or physiology to use. In this regard, companies of all sizes can implement the RNLE in all manner of ways ranging from simple pencil and paper analyses for small companies to customized software and instrument-assisted data collection for large organizations.

1.3 Research Outcomes-Impact

The RNLE and continuous exposure-response relationships provide a basis for detailed biomechanical exposure measurement and continuous improvement. Similar to quantitative quality control programs, this type of comprehensive and systematic approach to occupational LBP prevention and intervention can be expected to reduce workers' compensation costs, lost time due to LBP and short- and long-term LBP-related disability within companies that choose to use the strategy and tools.

Further development of the RNLE is warranted and in particular adaptations that accommodate one-handed-lifting, interactions between reaching and twisting, and between twisting and bending should be developed and tested.

Psychosocial factors might play an important role in modifying risk of LBP and/or modifying the effects of physical exposure. Psychosocial factors should be specifically studied in the presence of rigorously measured physical exposures.

Past history of LBP is strong risk factor that has the potential to confound associations between other factors and LBP outcomes. Prospective cohort studies of workers without prior history of LBP are needed to confirm or clarify the exposure-response associations reported here.

Intervention studies based on the findings of this and other similar studies are urgently needed to clarify injury-reduction strategies and to set future research and development directions.

Section 2: Scientific Report

2.1 Background

Low back pain (LBP) is a common health problem in the general population – affecting 80-85% of people in their lifetime[1] – is a frequent cause of activity limitation and lost workdays,[2-4] and is one of the most common reasons for seeking health care.[3] Workplace back injuries account for 41% of all MSD cases and require a median of 7 days to recuperate.[5] The average cost of a back injury insurance claim is approximately $7,100.[6,7]

Literature suggests that LBP has a complex, multifactorial etiology. [8,9] LBP risk factors include (i) job physical exposures, (ii) worker demographics, (iii) past LBP history, (iv) psychosocial factors, and (v) hobbies and physical activities outside of work.[8-10] In spite of voluminous literature on LBP, there is a lack of consensus on the roles of individual, psychosocial and job physical factors in the pathogenesis of LBP.[11]

There is no consensual definition of LBP[12] other than the recently proposed operational case definition for chronic LBP.[13] Thus, prior studies of workplace LBP have used several different case definitions, and there is some evidence to suggest that the risk factors for LBP may vary with the case definition.[12,14,15] Further, LBP may lead to seeking care for LBP (SC-LBP) and lost time (i.e., missed work, LT-LBP), both of which may cause substantial economic burdens to employees and employers.[7,16,17] While LBP (pain alone) is frequently studied – often with imprecise measures of job physical exposure – only a few studies have investigated associations between biomechanical risk factors and SC-LBP and LT-LBP. Thus, there is a paucity of information on associations between quantified job physical factors and LBP, SC-LBP and LT-LBP. [9,12,14-16]

Many biomechanical risk factors have been suggested for LBP; [9] however, several problems have likely contributed to inconsistent findings reported in the literature. The problems include poorly quantified job physical exposures, and/or methodological limitations, such as: (i) use of job titles or self-reported physical exposure – resulting in imprecise exposure estimates and/or recall bias; (ii) use of a single job variable to estimate physical exposure, thus, ignoring effects from other physical exposure variables (e.g., trunk flexion, trunk rotation, lifting heavy weight, etc.); (iii) imprecise techniques to quantify complex physical exposures for tasks with varying weights, hand locations, and/or job rotation (e.g., average weight, time-weighted-average (TWA) weight); (iv) reliance on cross-sectional or case-control design; (v) inconsistent LBP case definitions; (vi) use of small and /or non-representative samples of workers and industries; and/or (vii) lack of adjustments for individual and psychosocial factors.[18-39] Possibly for these reasons, recent reviews of studies have concluded that there is conflicting evidence for associations between LBP and either heavy physical work or working with the trunk bent and/or in a twisted posture.[40,42]

2.1.1 LBP and Physical Exposure Risk Factors

Generally accepted physical exposure risk factors for LBP include biomechanical, work organizational and environmental factors such as: lifting, pushing/pulling, and/or carrying heavy loads; bending, twisting, frequent lifting, driving, prolonged standing/sitting, whole body vibration and trunk kinematics (trunk velocities and bending moments). [11, 12, 24, 26-30, 34, 35, 37, 38, 43-45] Use of a single job physical exposure variable to quantify biomechanical stressors ignores potential interactions between job physical exposure variables.[31, 32] *Index-based* methods or models combining two or more job physical exposure variables into a single measure of risk include: (i)

Revised NIOSH Lifting Equation (RNLE), (ii) load moment, frequent lifting of heavy weights, etc., (iii) maximum acceptable weights and forces, (iv) compressive and shear forces on spinal discs (biomechanical models), and (v) combination of dynamic three-dimensional trunk motions. [9, 14, 15, 18-23, 25, 36, 39, 46, 47-53]

2.1.1.1 The Revised NIOSH Lifting Equation (RNLE)

Among the index-based methods, the RNLE [51, 52] is perhaps the most commonly used job analysis method to quantify biomechanical stressors to the low back. [9, 14,15, 36, 39, 48-50, 54-62] The RNLE is a comprehensive model that combines seven different biomechanical stressors (weight of the object, horizontal location of hands, vertical location of hands, travel distance, twisting angle, frequency and duration of lifting, and type of grasp) into a single metric called the Lifting Index (LI) for simple tasks[52], Composite Lifting Index (CLI) for complex tasks,[52] and Cumulative Lifting Index (CULI) for multi-task jobs with job rotation. [63] A few investigations have reported an association between the LI and LBP [36, 39, 48-50, 58]; however, these used cross-sectional study designs and/or failed to adjust for important covariates. There are only three prospective studies reporting relationships between RNLE and LBP outcomes while adjusting for relevant covariates, and the total sample size for those studies is small. [9, 14, 15]

2.1.1.2 Job Organizational Factors

Many believe job rotation to be an effective strategy for preventing, or at least managing MSDs; however, it is not well studied. A recent systematic review of job rotation in manufacturing environments[64] found only weak evidence for a reduction in exposure. Nevertheless, multi-task jobs do pose challenges to quantifying physical exposure and could plausibly reduce daily cumulative exposure thus making job rotation a potentially important factor to study.

The RNLE is designed to study two-handed lifting and lowering. [52] However, one-handed lifting is common in industry. While there is no clear strategy to incorporate one-handed lifting into RNLE calculations the factor is important to consider as a potential confounder or effect modifier[65] when using the RNLE.

2.1.2 LBP and Non-Occupational Factors

Peak prevalence of LBP occurs between 45 to 64 years of age,[12, 66-69] females appear to be at increased risk for LBP but results are inconsistent,[8,9,12,41,69-72] obesity has a weak association with increased risk of LBP;[12,73-74] and smoking has inconsistent findings.[9,26] Past history of LBP is consistently associated with increased risk of LBP.[9,26,37,46,75]

2.1.3 LBP and Workplace Psychosocial Factors

Past studies have found inconsistent associations between workplace psychosocial factors and LBP.[9, 14, 15 29, 30, 37, 38, 75-81] Low work support, low job satisfaction and/or high work demand appear to have more consistent association with LBP compared to other workplace psychosocial factors. [9, 25, 26, 37, 67, 82-84]

2.2 Hypothesis and Specific Aims

The alternative hypothesis for this study was:

H1: There are associations between the Revised NIOSH Lifting Equation and/or other biomechanical lifting/lowering parameters and low-back-pain (LBP), seeking care for LBP (SC-LBP), and lost-time due to LBP (LT-LBP), while accounting for history of LBP, demographic, and psychosocial factors.

Specific Aims were to:

1. Develop a pooled dataset with worker specific information on: (i) LBP, SC-LBP and LT-LBP, (ii) detailed biomechanical stressors measured at the job, task, and subtask levels, (iii) personal factors (demographics, prior history of LBP), and (iv) psychosocial factors.
2. Calculate pooled baseline prevalence and average annual incidence rates for LBP, SC-LBP, and LT-LBP.
3. Estimate associations between prevalent cases of LBP, SC-LBP, and LT-LBP, and measures of biomechanical stressors (enumerated in Aim 4) adjusted for relevant covariates (age, gender, BMI, prior history of LBP, and psychosocial factors).
4. Perform primary analyses to estimate associations between incident cases of LBP, SC-LBP, and LT-LBP, and three measures of biomechanical stressors adjusted for relevant covariates (i.e., age, gender, BMI, prior history of LBP, and psychosocial factors). The three measures of biomechanical stressors are: (i) RNLE Peak Lifting Index (PLI, subtask analysis), (ii) RNLE Peak Composite Lifting Index (PCLI, task-analysis), and (iii) Cumulative Lifting Index using RNLE (CULI, a proposed, innovative method for job level analysis).
5. Perform secondary analyses to: (i) examine relationships between the three health outcomes and: (a) simple measures of biomechanical stressors (e.g., object weight, lifting frequency, load moment, trunk posture) (ii) compare the efficacy of other methods for assigning daily physical exposure to workers (Sequential Lifting Index (SLI), and Time-Weighted-Average CLI), and (iii) examine potential interactions between biomechanical stressors and covariates (i.e., age, gender, BMI and psychosocial factors).

2.2.1 Summary of Specific Aims Progress and Completion

<u>Specific Aim #1</u>

Raw data from the study sites were pooled after establishing compatible definitions for each variable. Demographic and health outcomes data for the 1,976 workers shared similar definitions and were easily combined. Psychosocial data had more limited compatibility. Seven questions were deemed compatible and merged. Outcomes data were merged where variable definitions matched. These definitions are described in Section 2.3.2.2 of Methods.

Physical exposure data from each site shared similar variables and constructs; however, contrary to initial expectations, the pre-existing summarized variables proved incompatible due to material differences in the underlying assumptions used by each site to create those variables. There were effectively three levels of physical exposure data: (1) sub-task level data that contained parameters for each lift/lower performed by a worker, (2) task level data that contained logical groups of sub-tasks and were typically performed for 15 or more minutes per day and (3) job level data that contained information about all the tasks that a worker performed in a given day or shift. However, these three levels were not present at each site in a consistent way.

To create fully compatible data, each site's information had to be expanded to the sub-task level to create true compatibility and then reduced into task and job level data using standardized definitions and procedures. This process resulted in 1.2 million unique sub-tasks that were then reduced into 2,480 unique tasks and finally into 1,650 unique jobs (We were unable to reconcile and make compatible the job information for 326 workers).

A further unforeseen challenge emerged while reconfiguring the raw data. Approximately 99% of individual lifts were two-handed, as expected from preliminary analyses. However, the approximately 1% of one-handed lifts affected more than one third of tasks and ultimately about 25% of jobs, albeit in very small doses. The biomechanics of one-handed lifting are not well studied[65] and the NIOSH Lifting Equation is not intended to analyze these one-handed lifts.[51] Thus additional preliminary studies were needed so that strategies to accommodate one-handed lifts could be developed and final data could be prepared for pooled analyses. After performing several sensitivity analyses, it was determined that one-handed lifts could be treated as if they they were performed two-handed for the purposes of this report.

Despite these unforeseen problems and substantial delays, all work for Specific Aim #1 was fully completed as proposed.

Specific Aim #2

Using merged data, prevalence and incidence rates for LBP, SC-LBP, and LT-LBP were calculated and are provided in Section 2.4.1. Prevalence rates have been published. Incidence rates are included in publications currently under review.

Analyses for Specific Aim #2 were fully completed as proposed. Publications and other dissemination are ongoing.

Specific Aim #3

Work for Aim #3 began by performing univariate analyses of demographic, psychosocial, and physical exposure variables. Residual plots of physical exposure were used to identify non-linearities and potential outliers that could be indicative of computation problems or otherwise introduce inappropriate biases into the analyses. All variables were analyzed with a-priori adjustment for age, gender, BMI and lifetime history of LBP (LBP Hx).

Preliminary findings revealed that facility and research site were predictive of physical exposure and some psychosocial factors. While intensity of physical exposure was expected to vary by study site (indeed, increasing the range of exposures was a primary motivation for pooling these data), more homogeneity was expected amonst other factors. The lack of homogeneity somewhat restricted certain analyses. For example, study site could not be used as random effect or fixed factor in models while also including psychosocial factors or presence of one-handed lifting and job rotation.

Ultimately fully adjusted models comparing sub-task, task, and job-level RNLE measures were developed that omitted adjustments for research site. Those analyses are presented in this report. Analyses of psychosocial factors have been published.[85] Aim #3 is fully complete. A strategy to disseminate the RNLE prevalence results is being developed.

Specific Aim #4

Subsequent to Aim #3, Aim #4 began with univariate analyses of physical exposure, personal, and psychosocial factors. Fully adjusted models comparing sub-task, task, and job-level RNLE

measures were developed and are presented in this report. Analyses for Aim #4 are complete. Publications are being drafted and will be submitted for publication in 2021.

Specific Aim #5

Aim #5 had three main goals: (1) examine individual lifting/lowering parameters to determine (a) independent association with outcomes of LBP and (b) simple interactions between parameters and outcomes of LBP, (2) compare alternative techniques to describe daily exposure using the RNLE, and (3) explore potential interactions between demographic, psychosocial factors, physical exposure, and outcomes of LBP.

Goal #1 – examine individual lifting/lowering parameters is fully complete and results are provided in this report. Goal #2 – compare alternative techniques to describe daily exposure using RNLE – is complete to the greatest extent feasible using these data. The proposed Aim included a comparison of the Sequential Lifting Index (SLI);[86] however, those analyses are not possible because the necessary data to create equivalent rotation schemes between research sites was not possible. TWA CLI and CULI were compared and the results are presented in this report. “Threshold” measures were proposed as synthetic measures to explore interactions between biomechanical risk factors. However, due to difficulties fully understanding the implications of the between research site heterogeneity of data, that aspect of Goal #3 was not complete at the time of this report and might prove impossible to ever complete proposed. Simple stratification of analyses on the basis of age, gender and BMI have shown no statistically significant results but here again it is not clear that the study has adequate power and sampling to state this negative finding with confidence especially given the heterogeneity of the underlying data. As an alternative to the “threshold” measures originally proposed, multi-factor, median-split and combined variables were created and analyses of those are provided in this report.

The research team is currently developing a dissemination plan for the completed Aim #5 results with an emphasis on publication of Goal #1 as the results of this study refute the findings of recent systematic reviews suggesting that biomechanical factors are not independent risk factors for LBP.[41, 42]

2.3 Methods

This study pooled data from four large prospective epidemiologic research studies conducted by: (i) the Ohio State University (OSU), (ii) the University of Utah (UU), (iii) the University of Wisconsin-Milwaukee (UWM), and (iv) NIOSH. The UWM and UU studies were conducted in parallel and used identical methods for all data collection. Workers in these studies were employed across a wide variety of industries (Table 1).

2.3.2 Developing a Pooled Dataset with Worker Specific Information

This study uses previously collected data on workers from 82 facilities representing 21 industries in the U.S. states of Illinois, Michigan, Ohio. Texas, Utah, and Wisconsin. These data were collected by three research teams: NIOSH, OSU, and UWM/UU (Some UWM data were collected by a team at Texas A&M University). Raw data on job physical exposures, outcomes of LBP, and individual and psychosocial covariates from NIOSH, OSU, and UWM/UU were combined into several datasets. Combined data were then exhaustively data-checked for integrity. Two types of data checks were performed: (i) a check for logical and data-entry/processing errors, and (ii) analytical checks to challenge the validity of common variable

definitions between the sites. Combined data were de-identified and protected health information were removed to greatest extend feasible. De-identified "gold master" datasets were created and provided to each of the sites (and American University, AU) for analyses.

Table 1: Summary of types of industries studied by the three sites

Industry	UWM/ UU	OSU	NIOSH	Industry	UWM/ UU	OSU	NIOSH
Airbag manufacturing	X			Metal parts manufacturing	X		
Automotive parts manufacturing	X			Office chair manufacturing	X		
Automotive parts distribution		X		Office work	X		
Book packaging & distribution	X			Paint manufacturing	X		
Clothing distribution center		X		Plastic parts manufacturing	X		
Commercial lighting mfg.	X			Repackaging operations	X		
Cosmetic manufacturing	X			Salt manufacturing	X		
General merchandise dist.		X		Salt packaging	X		
Grocery warehousing & dist.	X	X		Small engine manufacturing	X		
Lawnmower & equipment mfg.	X			Dryer mfg. & assembly			X
Meat processing	X						

2.3.2.1 Physical Exposure Measurements

All three sites collected the worker's job physical exposure data in the field using direct measurements and video observations (OSU used Low Back Moment Monitors [35]). UWM and UU collected data on each worker, OSU and NIOSH collected data on a sample of workers performing each job. All three sites had data available for each lift/lower performed by the workers. These data included object weight, horizontal locations of hands, vertical locations of hands, travel distance, asymmetric angle, type of grasp, frequency of lifting/lowering, cycle time, duration of task, duration of shift, and trunk postures. [9,14,15,35,39] These raw data were first expanded to create discrete measurements for each lift/lower performed by a worker (i.e., sub-tasks with each sub-task representing an individual lift or lower). This process created truly compatible physical exposure information across the sites. As a part of this process RNLE Frequently Independent Lifting Indexes (FILIs) were calculated for each sub-task. Next, sub-task level data were reduced to task-level data using the RNLE composite lifting index (CLI) algorithm, calculating total lifts/lower per minute for the task based on total task duration, and taking the peak (i.e., presumed most stressful) values for parameters such as weight, horizontal distance, and twisting. Finally, task-level data were reduced into job-level data using information about workers job rotation schemes, where applicable. For those workers with job rotation, RNLE CLIs were combined into CULI using the CULI algorithm.[63] For workers with no job rotation CULI was set equal to CLI for the single task performed. In addition, peak CLI (pkCLI) was recorded across all tasks performed by a worker, total lifting frequency across all tasks was calculated, and overall peak for lifting/lowering parameters such as weight, horizontal location, and twisting were recorded.

To facilitate Aim #5 analyses, TWA CLI was also calculated at the job-level. Parameters from the RNLE were assumed to be proxies for certain aspects of task performance. Weight lifted as assumed to be a proxy for “load”, horizontal location of hands was assumed as a a proxy for “reaching”, vertical location was assumed as a proxy for “bending” (since full-squat lifting is rarely used regularly in real-world working environments), and asymmetric angle was assumed as a proxy for “twisting. Composite variables of individual lift/lower parameters were created by splitting parameter variables at their median and creating 4-level “interacted” categories. For example: peak asymmetric angle (“twist”) and peak horizontal location (“reach”) were median split and combined to create four categorical levels consisting of (1) low reach and low twist, (2) extended reach only, (3) extended twist only, and (4) extended reach and extended twist. Based on preliminary analyses and professional judgement, all parameters were interacted with both weight (“load”), and asymmetric angle (“twist”). In addition, vertical location (“bend”) and total frequency were also combined.

2.3.2.2 Individual and Psychosocial Measurements

Questionnaire data included baseline information on age, gender, history of episodes of LBP lasting four or more weeks over the prior year, and history of LBP lasting four or more weeks over lifetime (LBP Hx). Body Mass Indices (BMIs) were calculated from measured heights and weights.

Psychosocial measures were assessed via baseline questionnaires. Seven psychosocial measures were deemed compatible and pooled between the research sites. Responses to each measure were categorized into three to five levels depending on the number of potential responses.[85]

Compatible questions used in this study were:

1. How much influence or control you have over the variety of tasks you perform? (Very little, A little, Moderate amounts, Much, Very much)

2. How much influence or control you have over the order in which you perform tasks or work? (Very little, A little, Moderate amounts, Much, Very much)

3. How much influence or control you have over the pace of work, that is how fast or slow you work? (Very little, A little, Moderate amounts, Much, Very much)

4. How much influence or control you have over the extent to which you can work ahead and take a short break during work hours? (Very little, A little, Moderate amounts, Much, Very much)

5. Receiving support from immediate supervisor on the job. (Almost always, Some of the time, Hardly ever)

6. Receiving support from coworkers on the job. (Almost always, Some of the time, Hardly ever)

7. All in all, how satisfied are you with your job? (Very satisfied, Somewhat satisfied, A little satisfied, Not at all satisfied)

For all psychosocial variables, the adjacent most “positive” or “good” categories were combined to form stable reference categories. Details are described in Thiese et al.[85]

2.3.2.3 Health Outcomes Measurements

All sites conducted surveys and interviews at baseline and then again monthly (UWM/UU), after 6 months (OSU), or annually (NIOSH) throughout follow-up. Case definitions for LBP, SC-LBP and LT-LBP are provided in Table 2.

For prevalence, all workers who met one or more of the case definitions and who did not report their LBP as being caused by an accident were classified as prevalent cases. For incidence, those workers who did not have LBP at baseline and who received at least one followup visit were eligible for incident analyses of LBP. For incidence of SC-LBP and LT-LBP, all workers who were not prevalent at baseline and who received followup were incident eligible. Workers who developed LBP during follow-up and reported that LBP as being caused by an accident were removed from the study on the day of the reported accident and recorded as non-cases as of their last known non-accident followup report.

Table 2. Case definitions for LBP, SC-LBP and LT-LBP

Outcome	Definition	Exclusion Criteria for incident cases
Back Pain (LBP)	Regional LBP (i.e., lumbosacral area), of any pain intensity, and lasting ≥ 7 days in the last 12 months.	(i) Met case definition at baseline, OR (ii) LBP episode was due to an accident.
Seeking care for LBP (SC-LBP)	Saw a healthcare provider (a doctor, nurse, physical therapist, chiropractor or other health care provider) for back symptoms ≥ 1 time in the last 12 months.	(i) Met case definition at baseline, OR (ii) LBP episode was due to an accident.
Lost time (missing work) due to LBP (LT-LBP)	Missed work for ≥ 1 day due to LBP in the last 12 months.	(i) Met case definition at baseline, OR (ii) LBP episode was due to an accident

2.3.4 Calculating Pooled Baseline Prevalence and Average Annual Incidence Rates for LBP, SC-LBP, and LT-LBP

Baseline prevalence and crude average annual incidence rates (i.e., new cases per 100 person-years (P-Y)) were calculated for LBP, SC-LBP, and LT-LBP using case definitions from Table #2. For incidence rate calculations, prevalent cases were excluded. Gender-, and age-specific incidence rates were calculated.

2.3.5 Associations Between Psychosocial Factors and LBP, SC-LBP, and LT-LBP

For prevalence analyses, age, gender, BMI, smoking status and CULI (as an unmodified continuous measure) were considered as a-priori confounders to each of the seven psychosocial factors in the study. Frequencies and percentages were calculated for categorical variables. Correlations and Cronbach Alpha statistics were calculated for relationships between psychosocial variables. Logistic regression was used to calculate crude and adjusted odds ratios (ORs) and 95% confidence intervals (CI). Psychosocial factors were dichotomized to

assess relationship between individual psychosocial factors and age, sex, BMI, and company tenure. Potential confounders were adjusted using multivariable logistic regression.[85]

2.3.6 Estimating Exposure-Response Between the RNLE and Prevalent Cases of LBP, SC-LBP and LT-LBP

Logistic regression was used to determine odds ratios and 95% confidence intervals for the CULI, pkCLI, and FILI, and prevalent cases of LBP, SC-LBP, and LT-LBP after adjusting for covariates. The initial group of covariates a-priori included age, gender, BMI, and lifetime history of LBP (LBP Hx). Covariate psychosocial factors were selected using a best subsets approach with minimized corrected AIC values as the parameter to determine the optimal covariate model.[86, 87] A-prior factors were forced into all candidates models.

Null model (i.e., no variables, only outcome) residual plots from univariate analyses of CULI, pkCLI, and FILI were used to determine if non-linear exposure-responses were present. To account for non-linearity, linear splines with a single knot were used.[88] Knots were placed at the nearest percentile to the observed inflection point with the restriction that knots were placed on 5% intervals. All three RNLE measures showed marked non-linear responses with attenuation of risk at higher exposures. For prevalence analyses, attenuation began between the 70th and 95th percentile of data depending on the measure and the outcome.

2.3.7 Estimating Exposure-Response Between the RNLE and Incident Cases of LBP, SC-LBP and LT-LBP

For incident eligible workers, time from study enrollment to first occurrence of the LBP, SC-LBP, and LT-LBP was modeled using Cox proportional hazard (PH) regression.[89] Workers lost to follow-up prior to developing an incident case were censored as non-cases on the last date they contributed data. Hazard ratios (HR) and corresponding 95% confidence intervals (95% CI) were calculated.

CULI, pkCLI, and FILI were were treated as time-varying covariates and all variables were treated as continuous wherever possible.[88]

Similar to prevalence analyses, the functional form of each RNLE measure was examined using Martingale residual plots.[90] A null PH model (i.e., no variables, only outcome) was fit and the resulting Martingale residuals were plotted against each of the continuous RNLE variables as well as age and BMI. Smoothed plots of the residuals provided approximate shapes of the association between the log HR and the continuous measure.[90] Both loess and cubic smoothing splines were used as means of estimating distribution shapes, as different smoothing methods may suggest different functional forms within PH models.[91]

Where non-linearities were apparent, linear splines with a single knot were used in a manner consistent with that described for prevalence analyses. When no transformations were suggested, continuous variables were treated as linear within the Cox regression models.

Age and BMI showed no apparent non-linearity. All three measure of RNLE showed smooth increases followed by attenuation of risk between the 50th and 95th percentile depending on the measure and the outcome.

Covariates were a combination of a-prior factors: age, gender, BMI, and LBP Hx; and psychosocial factors. Psychosocial factors were selected using a best-subsets method as described in section 2.3.6.

2.3.8 Statistical Power

Power calculations were based on prospective analysis of incident cases in a Cox model. The basis for the calculation is the total of 1,223 incident-eligible subjects and 471, 228, and 128 incident cases of LBP, SC-LBP, and LT-LBP, respectively. The calculations further assumed 80% power, two-sided tests at the $p<0.05$ significance level and that the exposure variable had R-squared = 0.2 when regressed on the covariates. Minimum hazard ratios likely to be detected for LBP, SC-LBP, and LT-LBP were 1.13, 1.26 and 1.34, respectively, per 1 standard deviation change in a continuous exposure measure. Power to detect a hazard ratios of 1.8 or larger per 1 standard deviation change in exposure was effectively 100% for all three outcomes. (Power analyses performed using the PASS statistical software).[92]

2.4 Results and Discussion

The three studies had combined, total enrollment of 1,976 workers. Of those 1,976 workers, 1,650 (83.5%) completed both health and physical exposure baseline assessments, and had sufficient information about their physical exposures to successfully merge sub-task level (i.e., individual lift/lower) data. Multi-task jobs were performed by 395 of the workers (i.e., workers had job rotation), while the remaining 1,271 worked mono-task jobs (i.e., performed only one task for their entire work shift). The 395 workers with multi-task jobs performed a total of 1,225 tasks, i.e., they rotated to an average of 3.1 tasks/worker (median = 2, range: 2–11) during their work day, with a vast majority (82%) rotating to between two and four tasks per day.

2.4.1 Pooled Prevalence and Incidence Rates for LBP, SC-LBP, and LT-LBP

Of the 1,976 total workers in the study, 1,929 had fully complete health outcomes and demographic information and could be included in basic prevalence analyses. After excluding prevalent workers and workers lacking follow-up information, 971, 1081, and 1136 workers were available for incidence analyses of LBP, SC-LBP, and LT-LBP, respectively.

<u>Any Low Back Pain (LBP)</u>

At baseline, prevalence of LBP for the entire eligible cohort was 25.0% (483 of 1,929). Males were more likely than females to be prevalent with a prevalence ratio (PR) of 1.25 ($p = 0.02$). There was no statistical difference between cases and non-cases with regard to age or BMI ($p>0.22$).

There were 971 incident eligible workers who contributed 1,281.5 person-years (P-Y) of data. Among those, 471 workers developed LBP for an average annual incidence rate of 36.8 per 100 P-Y. Age was protective for LBP. Workers with age less than the median of 34.6 years had average incidence of 41.7 per 100 P-Y as compared to 32.6 per 100 P-Y for those above the median age ($p < 0.001$). There was no association between incidence of LBP and gender, or

BMI. Incident rate for those with no prior history of LBP was 36.4 compared to 45.7 for those with LBP history (p <0.001).

Seeking Care for LBP (SC-LBP)

The baseline prevalence of seeking care for LBP (SC-LBP) was 14.1% (272 of 1,927) and males and females were equally likely to be prevalent (p = 0.14). There was no difference between age (p = 0.54) or BMI (p = 0.12) for prevalent versus non-prevalent cases.

There were 1081 incident eligible workers who contributed 1,483.6 P-Y of data. Among those, 228 workers developed SC-LBP for an average annual incidence rate of 15.4 per 100 P-Y. There was no association between incidence of SC-LBP and age, gender, or BMI. Incident rate for those with no prior history of LBP was 15.1 compared to 19.2 for those with LBP history (p <0.001).

Lost Time due to LBP (LT-LBP)

The baseline prevalence of lost time due to LBP (LT-LBP) was 10.0% (192 of 1,929). Similar to LBP, males were more likely than females to be prevalent with a prevalence ratio (PR) of 1.51 (p = 0.03).

There were 1136 incident eligible workers who contributed 1,527.8 P-Y of data. Among those, 128 workers developed LT-LBP for an average annual incidence rate of 8.4 per 100 P-Y. There was no association between incidence of SC-LBP and age, gender, or BMI. Incident rate for those with no prior history of LBP was 8.2 compared to 11.2 for those with LBP history (p <0.001).

2.4.2 Exposure-Response for Revised NIOSH Lifting Equation

2.4.2.1 RNLE and Prevalence of LBP, SC-LBP, and LT-LBP

Physical exposure estimates from the RNLE were analyzed based on sub-task analyses (i.e., peak FILI), task-level analyses (i.e., peak CLI), and job-level analyses (i.e., CULI). All analyses were adjusted for age, gender, BMI, and the psychosocial factors of job satisfaction, supervisor support and control of the order of tasks performed. The SC-LBP models were also adjusted for the coworker support psychosocial factor as that variable was also selected during best-subsets covariate model building.

Initially, LBP Hx was forced into all multivariate models as an a-priori covariate. However, presence of LBP Hx in the models sharply reduced the effect of physical exposure while having only nominal to minimal effect on other covariates. This suggests that prior history of LBP is a confounder for the effects of physical exposure, at least amongst this cohort of workers. Thus, LBP Hx was removed from all models and then subsequently returned to reveal the extent of the confounding (see results and discussion below). The associations between LBP Hx (i.e., lifetime history of LBP lasting four or more weeks) ranged from OR = 7.8 for LT-LBP up to OR = 17.7 for LBP. Univariate results are shown in Table 3.

Table 3: Univariate Prevalence Analyses of Lifetime History of LBP Lasting Four or More Weeks

Outcome	Odds Ratio	95% CI	p-value	AIC
LBP	17.69	13.36 – 23.60	<0.001	1399.40
SC-LBP	9.91	7.41 – 13.32	<0.001	1185.26
LT-LBP	7.78	5.57 – 10.93	<0.001	955.92

RNLE measures (i.e., CULI, pkCLI, and pkFILI) all followed a similar pattern where risk increased as exposure increased up to a threshold, beyond which risk attenuated. For CULI and pkFILI the attenuation resulted in a statistical leveling of risk (i.e., no further statistical increase or statistical decrease in risk). For pkCLI the attenuation tended to result in a statistical decrease in risk above the threshold. Thresholds were selected based on examination of null model residual plots and were placed on percentiles. These thresholds were used as knot points in linear spline models. Table 4 shows a summary of knots, percentiles, and odds ratios at inflection points for the RNLE measures. Odds ratios are based on results reported in Tables 5 to 7, below.

The principle reason for the attenuation in risk appears to be sparce exposure and case information in the long right-hand tail of the exposure distributions. Occasional very large RNLE values might be associated with infrequent lifts that nonetheless results in very large lifting indexes, or could be the results of sampling or other error. Regardless the cause, CULI is most affected by the skew in measurement because it incorporates all subtasks and all tasks.

Table 4: Summary of Knots, Percentiles, and ORs at Knots for RNLE and Prevalence of LBP Outcomes

RNLE Measure	LBP			SC-LBP			LT-LBP		
	Knot	%ile	OR[A]	Knot	%ile	OR[A]	Knot	%ile	OR[A]
CULI	4.7	85th	3.1	4.3	75th	7.6	4.0	70th	3.0
pkCLI	4.7	85th	3.5	4.1	75th	12.2	5.3	95th	3.2
pkFILI	4.2	95th	3.2	3.2	75th	5.5	3.2	75th	2.9

[A] Based on models that DO NOT include LBP Hx

Prevalence of LBP

All measures of RNLE were associated with increased risk of prevalence of LBP and all had comparable associations with peak ORs of 3.1, 3.5, and 3.2 for CULI, pkCLI, and pkFILI, respectively. Risk increased for pkFILI most quickly (slope = 1.316, 95%CI: 1.164 – 1.492 per unit) and most slowly for CULI (slope = 1.273, 95%CI: 1.135 – 1.432 per unit) (Table 5). These measures are derivatives of one another where pkCLI will always be larger than pkFILI and CULI will always be the same or larger than pkCLI. Thus, the steeper slope of pkFILI, despite its systematically lower scores suggests that exposures from peak lifts/lowers might be disproportionally indicating risk in this cohort.

Covariate associations with LBP were consistent across all models (Table 5). Risk of LBP increased with age at a rate of 1.4% per year of age. Thus, the OR for a 60-year-old compared to a 20-year-old was 1.7. Gender and BMI showed no association. Job satisfaction and supervisor support were both statistically associated with increase risk of LBP, but only supervisor support showed an uninterrupted dose-response relationship with peak ORs of about 2.0 for the category of “Hardly Ever”. Peak ORs for job satisfaction were higher at about 3.0 for the category of “Not at all”, but the adjacent category of “A Little” was not statistically associated

with LBP and showed a lower OR than the improved category of “Somewhat”. Control of task order appeared to show a trend of increasing risk with less control, but none of the categories was significant and the ORs were low.

Overall, pkCLI showed the lowest AIC score, followed by pkFILI and then CULI. This suggests that pkCLI has the strongest predictive potential. However, this might be the result of pkCLI having a statistically significant *decline* in risk above the knot of 4.7 whereas pkFILI and CULI both showed statistically level risk above their respective knot points.

Table 5: Analyses of Peak FILI (subtask), Peak CLI (task), and CULI (job), and Prevalence of Any Low-Back-Pain (LBP)

Factor	Peak FILI (aic: 1749.15)	Peak CLI (1741.8)	CULI (aic: 1751.5)
RNLE Exposure	**≤4.2: 1.316 (1.164 – 1.492)**	**≤4.7: 1.304 (1.166 – 1.461)**	**≤4.9: 1.273 (1.135 – 1.432)**
- 2nd Spline Leg	>4.2: 0.497 (0.178 – 1.388)	**>4.7: 0.666 (0.510 – 0.870)**	>4.9: 0.944 (0.868 – 1.026)
Age (continuous)	**1.014 (1.002 – 1.025)**	**1.014 (1.003 – 1.025)**	**1.014 (1.004 – 1.025)**
Gender			
- Female	1.00	1.00	1.00
- Male	1.13 (0.84 – 1.53)	1.10 (0.82 – 1.49)	1.12 (0.83 – 1.51)
BMI (continuous)	0.994 (0.974 – 1.013)	0.994 (0.974 – 1.014)	0.992 (0.973 – 1.012)
Job Satisfaction			
- Very Satisfied	1.00	1.00	1.00
- Somewhat	**1.42 (1.06 – 1.91)**	**1.43 (1.07 – 1.92)**	**1.42 (1.06 – 1.91)**
- A little	1.28 (0.86 – 1.91)	1.27 (0.85 – 1.88)	1.26 (0.85 – 1.87)
- Not at all	**2.98 (1.62 – 5.47)**	**2.94 (1.60 – 5.38)**	**3.00 (1.64 – 5.50)**
Supervisor Support			
- Almost Always	1.00	1.00	1.00
- Some Time	**1.64 (1.26 – 2.13)**	**1.62 (1.26 – 2.10)**	**1.64 (1.26 – 2.12)**
- Hardly Ever	**2.05 (1.39 – 3.01)**	**1.99 (1.35 – 2.92)**	**2.00 (1.36 – 2.93)**
Control Order			
- V. Much/Much	1.0	1.0	1.0
- Moderate	0.99 (0.73 – 1.33)	1.00 (0.74 – 1.34)	0.99 (0.73 – 1.33)
- A Little	1.13 (0.78 – 1.62)	1.15 (0.79 – 1.65)	1.10 (0.76 – 1.59)
- Very Little	1.15 (0.84 – 1.58)	1.16 (0.84 – 1.58)	1.19 (0.87 – 1.62)

***BOLD** indicates significant at $p \leq 0.05$

Prevalence of SC-LBP

All measures of RNLE were associated with increased risk of SC-LBP and ORs were higher for SC-LBP than the other outcomes (Table 6). However, unlike LBP (and LT-LBP, see below), the ORs were not comparable across all RNLE measures. The highest peak OR was for pkCLI with OR=12.2. pkFILI had the lowest peak OR with 5.5. The relatively “low” OR for pkFILI is likely due, in part, to its knot being reduced to the 75th percentile as compared to the 95th for LBP. However, this only partly explains the discrepancy as the same circumstance is true or LT-LBP and the ORs across those models are comparable (Table 4).

Covariates showed small or no association with increased risk of SC-LBP (Table 6). Age suggested increased risk with increased age; however, the association was not significant. Nor were gender or BMI associated with SC-LBP. The pattern of association for job satisfaction was similar to that observed for LBP, but none of the categories was significant. Supervisor support showed some statistically significant increased risk for the category of "some time" with ORs of about 1.75; however, there was no apparent dose-response relationship. Base on best-subsets selection, SC-LBP also included coworker support as a covariate. While there was a hint of dose-response association for coworker support, none of the categories was significant and ORs were modest to low. Control over task order showed no associations.

Table 6: Analyses of Peak FILI (subtask), Peak CLI (task), and CULI (job), and Prevalence of Seeking Care for LBP (SC-LBP)

Factor	Peak FILI (aic: 1346.30)	Peak CLI (1328.01)	CULI (1347.71)
RNLE Exposure	**≤3.2: 1.706 (1.391 – 2.11)**	**≤4.1: 1.842 (1.548 – 2.214)**	**≤4.3: 1.603 (1.359 – 1.906)**
- 2nd Spline Leg	>3.2: 1.106 (0.777 – 1.576)	**>4.1: 0.717 (0.566 – 0.910)**	>4.3: 0.933 (0.844 – 1.032)
Age (continuous)	1.010 (0.997 – 1.023)	1.012 (0.999 – 1.025)	1.010 (0.997 – 1.023)
Gender			
- Female	1.00	1.00	1.00
- Male	0.85 (0.60 – 1.22)	0.80 (0.56 – 1.14)	0.85 (0.60 – 1.22)
BMI (continuous)	0.987 (0.963 – 1.011)	0.991 (0.966 – 1.015)	0.988 (0.964 – 1.012)
Job Satisfaction			
- Very Satisfied	1.00	1.00	1.00
- Somewhat	1.11 (0.79 – 1.58)	1.11 (0.79 – 1.58)	1.11 (0.79 – 1.56)
- A little	0.88 (0.53 – 1.42)	0.86 (0.52 – 1.40)	0.85 (0.52 – 1.38)
- Not at all	1.74 (0.84 – 3.47)	1.68 (0.81 – 3.37)	1.76 (0.85 – 3.52)
Supervisor Support			
- Almost Always	1.00	1.00	1.00
- Some Time	**1.77 (1.29 – 2.44)**	**1.72 (1.25 – 2.37)**	**1.74 (1.27 – 2.40)**
- Hardly Ever	1.61 (0.98 – 2.59)	1.48 (0.90 – 2.39)	1.50 (0.93 – 2.41)
Coworker Support			
- Almost Always	1.00	1.00	1.00
- Some Time	1.12 (0.82 – 1.53)	1.14 (0.84 – 1.55)	1.15 (0.84 – 1.56)
- Hardly Ever	1.29 (0.78 – 2.10)	1.34 (0.80 – 2.19)	1.31 (0.97 – 2.14)
Control Order			
- V. Much/Much	1.0	1.0	1.0
- Moderate	0.98 (0.69 – 1.39)	0.98 (0.69 – 1.40)	0.96 (0.67 – 1.37)
- A Little	1.03 (0.65 – 1.59)	1.07 (0.68 – 1.66)	0.99 (0.63 – 1.52)
- Very Little	1.06 (0.73 – 1.54)	1.05 (0.72 – 1.53)	1.08 (0.74 – 1.57)

***BOLD** indicates significant at $p \leq 0.05$

Similar to LBP, pkCLI showed the lowest AIC score, followed by pkFILI and then CULI. This, again, suggests that pkCLI had the strongest predictive potential. Again there is the caveat that pkCLI had a statistically significant *decline* in risk above the knot whereas pkFILI and pkCLI did not. This might have resulted in the superior AIC score.

Prevalence of LT-LBP

All measures of RNLE were associated with increased risk of LT-LBP and all had comparable associations with peak ORs of 3.0, 3.2, and 2.9 for CULI, pkCLI, and pkFILI, respectively. Consistent with both LBP, risk increased most quickly with an increase in pkFILI. For LT-LBP, pkCLI showed the lowest rate of increased risk at about 25% per unit increase (Table 7). This might be due to the relatively higher knot point of 5.3 (95th percentile) compared to 4.1 and 4.3 (75th and 85th percentile for SC-LBP and LBP, respectively). A noteworthy change for RNLE associations with LT-LBP was that pkCLI no longer showed a statistically significant decline in risk above the knot. There was still a sharp attenuation of risk but similar to CULI and pkFILI, there was no statistical increase or decrease in risk above the knot. This change is likely the result of: (a) the increased percentile of the knot for pkCLI, and (b) a couple non-cases of SC-LBP at very high pkCLI exposures.

Table 7: Analyses of Peak FILI (subtask), Peak CLI (task), and CULI (job), and Prevalence of Lost Time due to LBP (LT-LBP)

Factor	Peak FILI (aic: 1050.45)	Peak CLI (1044.86)	CULI (1051.9)
RNLE Exposure	**≤3.0: 1.399 (1.114 – 1.780)**	**≤5.3: 1.247 (1.079 – 1.445)**	**≤4.5: 1.318 (1.077 – 1.634)**
- 2nd Spline Leg	>3.2: 1.066 (0.685 – 1.658)	>5.3: 0.333 (0.106 – 1.044)	>4.5: 0.863 (0.726 – 1.027)
Age (continuous)	0.999 (0.984 – 1.015)	0.998 (0.982 – 1.013)	0.999 (0.984 – 1.015)
Gender			
- Female	1.00	1.00	1.00
- Male	1.19 (0.77 – 1.88)	1.25 (0.82 – 1.98)	1.24 (0.80 – 1.92)
BMI (continuous)	0.995 (0.966 – 1.023)	0.996 (0.968 – 1.024)	0.995 (0.967 – 1.028)
Job Satisfaction			
- Very Satisfied	1.00	1.00	1.00
- Somewhat	1.51 (0.98 – 2.36)	1.51 (0.98 – 2.36)	1.48 (0.97 – 2.32)
- A little	1.28 (0.71 – 2.29)	1.26 (0.70 – 2.25)	1.23 (0.69 – 2.19)
- Not at all	**3.24 (1.50 – 6.79)**	**3.20 (1.49 – 6.70)**	**3.08 (1.43 – 6.42)**
Supervisor Support			
- Almost Always	1.00	1.00	1.00
- Some Time	**1.74 (1.19 – 2.57)**	**1.75 (1.20 – 2.58)**	**1.71 (1.17 – 2.52)**
- Hardly Ever	**2.45 (1.45 – 4.08)**	**2.44 (1.45 – 4.06)**	**2.35 (1.40 – 3.90)**
Control Order			
- V. Much/Much	1.0	1.0	1.0
- Moderate	1.17 (0.78 – 1.77)	1.17 (0.77 – 1.76)	1.16 (0.76 – 1.75)
- A Little	1.17 (0.69 – 1.94)	1.17 (0.69 – 1.93)	1.14 (0.67 – 1.88)
- Very Little	0.97 (0.61 – 1.52)	0.95 (0.60 – 1.49)	0.74 (0.61 – 1.53)

***BOLD** indicates significant at $p \leq 0.05$

There were no apparent or statistical associations between age, gender, or BMI, and LT-LBP. Associations for psychosocial factors were similar to LBP insofar as supervisor support showed a dose-response relationship with OR of approximately 2.4 for the category of “hardly ever”; and job satisfaction showed increased risk for the category of “not at all” with ORs of about 3.2, but no apparent dose-response relationship. However, whereas control task order hinted at a dose-

response relationship with LBP, there was no apparent trend with LT-LBP (i.e., LT-LBP was more consistent with SC-LBP for the control task variable).

Overall, pkCLI again showed the lowest AIC score and CULI the highest. Unlike the LBP and SC-LBP models, pkCLI did not show a statistically significant reduction in risk above the knot and so that circumstance cannot explain the lower AIC within this outcome.

Summary of Prevalence Analyses

Across the RNLE exposure measures and across the LBP outcomes, pkCLI consistently showed the the best performance with regard to AIC score. This is contrary to the a-prior expectation that CULI would perform the best because it included the most information about physical exposure. In fact, CULI consistently performed the worst in terms of AIC. Nonetheless, CULI did show strong association with p<0.001 for all three outcomes (Table 8).

Among demographic covariates, age was associated only with LBP. Age trended towards significance for SC-LBP but the p-values were low (p=0.117 in the model with CULI, Table 8). Gender and BMI were not associated.

For psychosocial factors, supervisor support showed consistent association with outcomes and a mostly consistent dose-response relationship. Job satisfaction was inconsistent in association with the main effect being the worst category and then only inconsistently across the outcomes (Table 8).

Table 8: Summary of Prevalence Analyses based on CULI (i.e., job) Exposure for Outcomes of LBP

Factor	LBP		SC-LBP		LT-LBP	
RNLE Exposure						
- CULI	**p < 0.001**	****	**p < 0.001**	****	**p < 0.001**	****
Age (continuous)[A]	**p = 0.009**	***	p = 0.117		p = 0.936	
Gender[A]	p = 0.456		p = 0.378		p = 0.344	
BMI (continuous)[A]	p = 0.455		p = 0.329		p = 0.749	
Job Satisfaction[B]	**p = 0.006**	***	p = 0.669		**p = 0.031**	**
Supervisor Support[B]	**p < 0.001**	****	**p = 0.007**	***	**p < 0.001**	****
Coworker Support[B]	---		p = 0.211		---	
Control Order[B]	p = 0.260		p = 0.688		p = 0.933	

****: p<0.001 ***: p<0.01 **: p<0.05 *: p<0.10

[A] A-priori factor forced into all models

[B] Factor selected using best-subset approach

Lifetime history of LBP lasting four or more weeks (LBP Hx) was strongly associated with prevalence of LBP outcomes (Table 3) and thus excluded from models reported in Tables 5 to 7. LBP Hx was forced into the pkCLI models (i.e., the best performing RNLE models) for each of the three outcomes to show the relative effect LBP Hx has on physical exposure and other covariates. These results are shown in Table 9.

Table 9: Summary of Prevalence Analyses based on pkCLI Exposure and adjusted for Lifetime History of LBP Lasting Four or More Weeks

Factor	LBP	SC-LBP	LT-LBP
RNLE Exposure	≤4.7: 1.121 (0.984 – 1.279)	**≤4.1: 1.584 (1.319 – 1.917)**	≤5.3: 1.129 (0.970 – 1.317)
- 2nd Spline Leg	>4.7: 0.819 (0.627 – 1.071)	>4.1: 0.812 (0.631 – 1.045)	>5.3: 0.523 (0.214 – 1.283)
Age (continuous)	**1.013 (1.000 – 1.026)**	1.007 (0.993 – 1.021)	0.993 (0.977 – 1.009)
Gender			
- Female	1.00	1.00	1.00
- Male	0.90 (0.63 – 1.27)	**0.66 (0.45 – 0.98)**	1.10 (0.70 – 1.77)
BMI (continuous)	1.001 (0.978 – 1.025)	0.995 (0.968 – 1.022)	1.002 (0.971 – 1.032)
LBP Hx	**17.13 (12.69 – 23.34)**	**9.34 (6.81 – 12.90)**	**6.79 (4.76 – 9.74)**
Job Satisfaction			
- Very Satisfied	1.00	1.00	1.00
- Somewhat	1.27 (0.90 – 1.79)	0.95 (0.65 – 1.39)	1.33 (0.85 – 2.12)
- A little	1.07 (0.66 – 1.73)	0.67 (0.38 – 1.16)	1.07 (0.58 – 1.97)
- Not at all	**2.82 (1.35 – 5.77)**	1.33 (0.58 – 2.92)	**2.62 (1.13 – 5.88)**
Supervisor Support			
- Almost Always	1.00	1.00	1.00
- Some Time	**1.43 (1.05 – 1.96)**	**1.53 (1.08 – 1.97)**	**1.53 (1.02 – 2.30)**
- Hardly Ever	**1.60 (1.00 – 2.54)**	1.16 (0.67 – 1.74)	**1.97 (1.12 – 3.42)**
Coworker Support			
- Almost Always	---	1.00	---
- Some Time	---	1.24 (0.88 – 1.74)	---
- Hardly Ever	---	1.31 (0.74 – 2.26)	---
Control Order			
- V. Much/Much	1.0	1.0	1.0
- Moderate	0.82 (0.58 – 1.18)	0.86 (0.58 – 1.28)	1.08 (0.67 – 1.68)
- A Little	0.88 (0.56 – 1.35)	0.85 (0.51 – 1.38)	0.99 (0.63 – 1.69)
- Very Little	0.69 (0.47 – 1.01)	0.71 (0.46 – 1.08)	0.65 (0.74 – 1.06)

***BOLD** indicates significant at $p \leq 0.05$

For all outcomes, peak OR for pkCLI was reduced by approximately one half. Without LBP Hx, peak ORs for pkCLI were 3.5, 12.2 and 3.2, for LBP, SC-LBP, and LT-LBP, respectively. With LBP Hx in the models, peak ORs for pkCLI were 1.7, 6.6, and 1.9, respectively. Thus ORs for pkCLI were reduced by approximately 40 to 50 percent (Tables 4 and 9). Further, pkCLI was no longer a statistically significant variable within the LBP and LT-LBP models.

Conversely, other covariates were mostly nominally or minimally affected. Age remained associated only with LBP. BMI continued to show no association. Supervisor support continued to show dose-response relationships with LBP and LT-LBP with only slightly decreased ORs. Similarly, job satisfaction continued to show association with LBP and LT-LBP for the worst category of “not at all”.

Some changes with covariates did occur and those changes were confined to the SC-LBP outcome. For SC-LBP, male gender became protective at OR = 0.67 (95%CI: 0.45 – 0.98), and the worst category of supervisor support, “hardly ever”, showed markedly reduced OR and no

statistical significance. This suggests that, within this cohort, males with history of LBP who sought care for their newly developed LBP hardly ever felt supported by their supervisors. While plausible, that explanation seems overly specific and thus this could be a circumstantial finding that is not generalizable to other populations

Overall, RNLE, and in particular pkCLI is associated with prevalence of LBP, SC-LBP, and LT-LBP with fairly strong peak ORs (ranged 2.9 to 12.2) even after adjusting for demographic and psychosocial factors. However, low-back history is a confounding factor for these associations and appears to substantially reduce the rate of increased risk for the exposure-response relationships. Lack of supervisor support is a consistent risk factor with or without history of LBP. This might suggest that broader work-organization factors play a strong role in prevalence of LBP outcomes.

2.4.2.2 RNLE and Incidence of LBP, SC-LBP, and LT-LBP

Primary incidence analyses proceeded in a similar fashion to prevalence analyses. All analyses were a-priori adjusted for age, gender, BMI, and LBP Hx. LBP Hx did not show the strong confounding effects in incidence analyses that it showed in prevalence analyses. Psychosocial factors were generally not associated with the LBP outcomes and perhaps for this reason each outcome had a slightly different set of psychosocial factors identified during best-subset covariate model building.

CULI, pkCLI, and pkFILI all showed non-linear associations with LBP, SC-LBP and LT-LBP. Knots for CULI were at the median across the three outcomes, whereas knots for pkFILI were at 95th percentile for all three outcomes. The main difference is knot placement appears to be the influence of outliers. Because pkFILI is inherently a "simple" measure of lift/lower biomechanics that is not encumbered by the physiological effects of frequency, the breadth of subtasks that make up a task (i.e., pkCLI score), nor the complexities of accounting for job rotation (i.e., CULI), its range is constrained and outliers are limited. Conversely, CULI is a complex measure and CULI scores become increasingly diffuse as they increase in magnitude. Thus, it is not clear whether the relatively low knot points for CULI are simply a reflection of complex distribution of data (which the linear splines at least partly account for, if there are underlying measurement errors or bad assumptions buried within the raw data, or if the model simply does not accurately characterize the true strains associated with high exposures. Any or all of these are plausible explanations by the similar exposure-response tendencies, but differing knot points between the RNLE measures. A summary of knot points, percentiles, and peak hazard ratios (HRs) are provided in Table 10.

Table 10: Summary of Knots, Percentiles, and HRs at Knots for RNLE and Incident LBP Outcomes

RNLE Measure	LBP			SC-LBP			LT-LBP		
	Knot	%ile	HR[A]	Knot	%ile	HR[A]	Knot	%ile	HR[A]
CULI	3.2	50th	1.5	3.2	50th	2.4	3.2	50th	2.1
pkCLI	5.1	90th	2.4	4.6	85th	2.3	3.7	65th	2.1
pkFILI	4.2	95th	2.5	4.2	95th	2.7	4.2	95th	2.5

[A] Based on models include LBP Hx

Incidence of LBP

All measures of RNLE were associated with increased risk of incidence of LBP. Peak HRs for pkCLI and pkFILI were comparable at about 2.5. The peak HR for CULI was lower at 1.5, mostly because the knot was at CULI=3.2 whereas the knots for pkCLI and pkFILI were at 5.1 (90th percentile) and 4.2 (95th percentile), respectively. The rate of increase was fastest for CULI (1.136 per unit) up to the knot point (Table 11). CULI and pkCLI both showed statistically level risk above the knot points, whereas pkFILI showed a statistically significant decrease in risk above the knot of 4.2 (and across the last 5% of data).

Table 11: Analyses of Peak FILI (subtask), Peak CLI (task), and CULI (job), and Incidence of Any Low-Back-Pain (LBP)

Factor	Peak FILI (aic: 4945.41)	Peak CLI (aic: 4950.98)	CULI (aic: 4948.65)
RNLE Exposure	**≤4.2: 1.124 (1.016 – 1.244)**	**≤5.1: 1.093 (1.009 – 1.185)**	**≤3.2: 1.136 (1.005 – 1.129)**
- 2nd Spline Leg	**>4.2: 0.425 (0.203 – 0.888)**	>5.1: 0.933 (0.811 – 1.072)	>4.9: 0.950 (0.901 – 1.001)
Age (continuous)	**0.986 (0.978 – 0.995)**	**0.985 (0.977 – 0.994)**	**0.985 (0.976 – 0.993)**
Gender			
- Female	1.0	1.0	1.0
- Male	0.93 (0.76 – 1.15)	0.90 (0.73 – 1.12)	0.94 (0.76 – 1.16)
BMI (continuous)	1.001 (0.987 – 1.016)	1.000 (0.986 – 1.015)	1.000 (0.986 – 1.015)
LBP Hx	**2.01 (1.30 – 3.10)**	**2.01 (1.30 – 3.11)**	**1.97 (1.27 – 3.04)**
Control Breaks			
- V. Much/Much	1.0	1.0	1.0
- Moderate	0.99 (0.75 – 1.31)	1.03 (0.78 – 1.36)	1.00 (0.76 – 1.32)
- A Little	1.01 (0.77 – 1.33)	1.05 (0.80 – 1.38)	1.04 (0.79 – 1.36)
- Very Little	1.19 (0.93 – 1.52)	1.21 (0.94 – 1.54)	1.20 (0.94 – 1.54)
Supervisor Support			
- Almost Always	1.0	1.0	1.0
- Some Time	1.05 (0.84 – 1.29)	1.05 (0.85 – 1.29)	1.03 (0.84 – 1.27)
- Hardly Ever	0.90 (0.64 – 1.28)	0.90 (0.64 – 1.28)	0.89 (0.63 – 1.26)
Coworker Support			
- Almost Always	1.0	1.0	1.0
- Some Time	1.12 (0.91 – 1.39)	1.14 (0.92 – 1.41)	1.13 (0.91 – 1.40)
- Hardly Ever	1.29 (0.95 – 1.77)	1.33 (0.97 – 1.81)	1.33 (0.98 – 1.82)

***BOLD** indicates significant at $p \leq 0.05$

A comparison of AIC scores showed that, unlike the prevalence models, pkCLI had the highest (i.e., worst) AIC score. When taken into account with the pkCLI also having the lowest rate of increased risk, it can be fairly stated that pkCLI performed the worst of the three RNLE measures with regard to risk of incident LBP. By AIC score alone, pkFILI performed the best, and while its slope was slightly less than CULI, the increase extended across a much wider range of data than CULI. Thus, for the outcome of LBP, pkFILI is the best of the RNLE measures for predicting risk (Table 11).

Age was *protective* for LBP with an HR of about 0.55 for a 60 year-old as compared to a 20 year-old. This association was effectively identical across all measures of RNLE, and is perhaps a strong indicator of the presence of health worker survivor effect (HWSE) within this cohort (Table 11).

Prior history of LBP was a consistent risk factor with HR of about 2.0 for all three outcomes. This is notably less increased risk than was observed for prevalence (Table 11).

Gender and BMI showed no association with increased risk. Neither did the included psychosocial factors of control over breaks, supervisor support, or coworker support (Table 11).

Incidence of SC-LBP

All measures of RNLE were associated with increased risk of SC-LBP. Similarly, all three measures showed increased risk as score increased followed by a statistical leveling of risk as score increased beyond the knot. CULI showed the fastest rate of increased risk (1.316 per unit) and pkCLI the slowest (1.271 per unit). However, peak HR was observed for pkFILI because the knot was at a relatively lower percentile for CULI (Table 12).

Table 12: Analyses of Peak FILI (subtask), Peak CLI (task), and CULI (job), and Incidence of Seeking Care for LBP (SC-LBP)

Factor	Peak FILI (aic: 2428.51)	Peak CLI (aic: 2431.22)	CULI (aic: 2429.52)
RNLE Exposure	**≤4.2: 1.271 (1.103 – 1.464)**	**≤4.6: 1.200 (1.060 – 1.358)**	**≤3.2: 1.316 (1.098 – 1.576)**
- 2nd Spline Leg	>4.2: 0.500 (0.228 – 1.098)	>4.6: 0.803 (0.629 – 1.024)	>3.2: 0.925 (0.849 – 1.009)
Age (continuous)	01.001 (0.989 – 1.013)	0.999 (0.988 – 1.011)	1.000 (0.998 – 1.011)
Gender			
- Female	1.0	1.0	1.0
- Male	0.93 (0.68 – 1.27)	0.92 (0.68 – 1.26)	0.95 (0.70 – 1.30)
BMI (continuous)	1.015 (0.996 – 1.034)	1.016 (0.985 – 1.035)	1.016 (0.996 – 1.035)
LBP Hx	**2.18 (1.34 – 3.57)**	**2.08 (1.28 – 3.40)**	**2.00 (1.22 – 3.27)**
Control Order			
- V. Much/Much	1.0	1.0	1.0
- Moderate	0.95 (0.67 – 1.34)	0.99 (0.70 – 1.39)	0.97 (0.68 – 1.36)
- A Little	0.95 (0.63 – 1.44)	0.99 (0.65 – 1.50)	0.98 (0.64 – 1.49)
- Very Little	1.29 (0.89 – 1.88)	1.32 (0.90 – 1.92)	1.37 (0.94 – 2.00)
Supervisor Support			
- Almost Always	1.0	1.0	1.0
- Some Time	1.10 (0.82 – 1.47)	1.08 (0.81 – 1.45)	1.07 (0.80 – 1.44)
- Hardly Ever	0.86 (0.52 – 1.43)	0.84 (0.50 – 1.40)	0.83 (0.50 – 1.39)

***BOLD** indicates significant at $p \leq 0.05$

Similar to incidence of LBP, pkFILI had the lowest AIC score and pkCLI the highest, suggesting that pkFILI is the superior predictive measure (Table 12).

Lifetime history of LBP (LBP Hx) was a significant risk factor in all three models with HR of approximately 2.10 (ranging from 2.00 for the CULI model, and 2.18 for the pkFILI model). All

other demographic and psychosocial measures (i.e., control of task order and supervisor support) showed no association with incidence of SC-LBP.

Incidence of LT-LBP

Similar to LBP and SC-LBP, all three RNLE measures were associated with increased risk of LT-LBP, and similar to SC-LBP, all three measures showed increased risk up to the knot followed by a statistically level risk above the knot. Rate of increased risk (i.e., slope) was comparable across all three measures, with CULI and pkFILI very similar at approximately 1.250 per unit. (Table 13).

AIC scores followed the same overall pattern as LBP and SC-LBP with pkFILI having the lowest AIC score and pkCLI having the highest. For LT-LBP AIC scores were fairly comparable, perhaps suggesting that all three models are approximately equal with regard to predictive ability for the outcome of LT-LBP (Table 13).

Similar to SC-LBP, only lifetime history of LBP showed association with LT-LBP with HRs of approximately 1.95. No other demographic covariates showed association, nor did the included psychosocial factor of control over task order.

Table 13: Analyses of Peak FILI (subtask), Peak CLI (task), and CULI (job), and Incidence of Lost Time due to LBP (LT-LBP)

Factor	Peak FILI (aic: 1435.26)	Peak CLI (aic: 1437.35)	CULI (aic: 1436.903)
RNLE Exposure	**≤4.2: 1.248 (1.039 – 1.498)**	**≤3.4: 1.217 (1.002 – 1.477)**	**≤3.2: 1.252 (1.200 – 1.800)**
- 2nd Spline Leg	>4.2: 0.457 (0.138 – 1.512)	>3.4: 0.872 (0.694 – 1.095)	>3.2: 0.928 (0.833 – 1.035)
Age (continuous)	0.991 (0.976 – 1.007)	0.989 (0.974 – 1.005)	0.990 (0.975 – 1.006)
Gender			
- Female	1.0	1.0	1.0
- Male	1.10 (0.72 – 1.69)	1.11 (0.72 – 1.70)	1.15 (0.75 – 1.76)
BMI (continuous)	1.007 (0.980 – 1.034)	1.007 (0.980 – 1.034)	1.007 (0.980 – 1.034)
LBP Hx	**2.03 (1.16 – 3.56)**	**1.93 (1.10 – 3.37)**	**1.93 (1.10 – 3.40)**
Control Order			
- V. Much/Much	1.0	1.0	1.0
- Moderate	1.26 (0.81 – 1.98)	1.30 (0.83 – 2.04)	1.30 (0.83 – 2.03)
- A Little	1.35 (0.80 – 2.27)	1.40 (0.83 – 2.36)	1.37 (0.81 – 2.30)
- Very Little	1.18 (0.69 – 2.03)	1.24 (0.73 – 2.12)	1.26 (0.74 – 2.16)

***BOLD** indicates significant at p ≤ 0.05

Summary of Primary Incidence Analyses

For all three outcomes the pkFILI produced the lowest AIC, suggesting that it is the best of the three for predicting risk of LBP, SC-LBP, and LT-LBP. However, it should be noted that all three measures were statistically associated with the three outcomes whereas, in general and with the exception of history of LBP, demographic and psychosocial factors were not. Similar to prevalence, this finding is contrary to the a-priori expectation that CULI would perform the best because it included the most information about physical exposures. However, whereas CULI

consistently performed the worst of the three measures in prevalence analyses, it was a close second to pkFILI in incidence analyses.

Overall, none of the three physical exposure measures performed as well in incidence analyses as they did in prevalence analyses with both smaller effect sizes and higher p-values. A summary of p-values for CULI across the three outcomes is provided in Table 14. This table shows that CULI was significant only at p<0.05 for LBP and SC-LBP and only trending towards significance (p=0.091) for LT-LBP when both spline leg one and two were included in aggregate. However, it should be noted that all factors proved statistically less reliable in incident analyses, including history of LBP that showed p-values greater than 0.001 for all models and greater than .01 for LT-LBP.

For incidence analyses psychosocial factors were inconsistently present and showed almost no association with the outcomes (Table 14). This is exactly opposite to prevalence analyses where psychosocial factors selected for each outcome were both consistent and at least somewhat strongly associated with increased risk. The lone exception was coworker support for the LBP outcome that trended towards significance with overall with p-values ≤0.10, but with no statistically significant levels and very modest HRs (≤1.33) (Tables 11 and 14).

Table 14: Summary of Incidence Analyses based on CULI (i.e., job) Exposure for Outcomes of LBP

Factor	LBP		SC-LBP		LT-LBP	
RNLE Exposure						
- CULI[A]	**p = 0.029**	**	**p = 0.040**	**	p = 0.091	*
Age (continuous)	**p ≤ 0.001**	****	p = 0.945		p = 0.214	
Gender	p = 0.540		p = 0.769		p = 0.531	
BMI (continuous)	p = 0.960		p = 0.112		p = 0.623	
LBP Hx	**p = 0.002**	***	**p = 0.006**	***	**p = 0.022**	**
Control Breaks[B]	p = 0.134		---		---	
Control Order[B]	---		p = 0.160		p < 0.294	
Supervisor Support[B]	p = 0.739		p = 0.721		---	
Coworker Support[B]	p = 0.070	*	---		---	

****: p<0.001 ***: p<0.01 **: p<0.05 *: p<0.10

[A] overall p-value from log-likelihood test for including vs. not including CULI in the model

[B] overall p-value based on test from trend between categories

As previously mentioned, LBP Hx was consistently and at least somewhat strongly associated with incidence of the three LBP outcomes. Unlike prevalence analyses, LBP Hx did not appear to confound measures of physical exposure when used in incidence analyses. It should be noted that many workers in this study had short participation time, either because the study was relatively short, or due to turnover. Further, prevalent workers were excluded even though some might have subsequently gone an extended period without LBP. It is possible that psychosocial and/or demographic factors would be associated with these LBP outcomes if *recurrence* of LBP were studied. It is similarly possible, if not likely, that the strength and magnitude of association between prior history of LBP and each outcome would increase if recurrent outcomes were allowed.

Overall, RNLE, and in particular pkFILI, and to a slightly lesser degree CULI, are associated with incidence of LBP, SC-LBP, and LT-LBP However, peak HRs are relatively low, ranging from between 1.5 to 2.7, despite relatively high incidence rates ranging from 8.4 to 36.8 per 100 P-Y. From this it is clear that, while physical exposure does appear to be consistently associated with increased risk of these outcomes, it is also not the primary explanatory factor.

2.4.2.3 Comparison of Techniques for Summarizing Multi-Task Jobs with the RNLE

A common technique to summarize daily physical exposure both in research and practice is time-weighted-average (TWA) exposure. This technique averages the exposures but gives relatively more weight to the task or tasks performed for longer durations. As described by Garg et al. in the CULI publication,[63] a potential problem with the TWA approach is that it assumes that high risk tasks can be mitigated by adding *more* work so long as that work is of lower exposure. To test how well TWA works, CULI was compared to TWA CLI after adjusting for the a-prior covariates of age, gender, BMI, and prior history of LBP. For these analyses simple linear as well as linear spline models were built.

As seen from the results in Table 15, neither TWA CLI nor CULI consistently performed better than the other. Simple linear TWA CLI did achieve statistical significance for LBP and SC-LBP whereas CULI did not achieve statistical significance in simple linear form. The main reason for this result appears to be that TWA CLI reduces a tendency for multi-task jobs to skew towards high scores, as happens with the CULI. This increasing gradient or "stretch" of scores with CULI appears to create attenuation of risk at higher levels than cannot be easily explained by HWSE or measurement/sampling error alone. It should be noted; however, that while TWA simple linear models were statistically associated with LBP and SC-LBP the HRs were almost trivially small at about 1.06 per unit increase in score. This shallow slope is the result of attenuation of risk at higher exposures and that attenuation likely is the result of HWSE within the cohort.

Table 15: Incident Analysis Comparison of CULI and TWA CLI

Factor	LBP	SC-LBP	LT-LBP
CULI			
Linear	*0.988 (0.956 – 1.021)* *aic: 5248.18*	1.010 (0.967 – 1.060) *aic: 2618.10*	0.989 (0.929 – 1.052) *aic: 1508.61*
Spline	**≤3.2: 1.146 (1.020 – 1.289)** >3.2: 0.954 (0.908 – 1.003) *aic: 5243.07*	**≤3.2: 1.355 (1.139 – 1.613)** >3.2: 0.945 (0.873 – 1.023) *aic: 2607.17*	**≤3.2: 1.260 (1.002 – 1.583)** >3.2: 0.928 (0.833 – 1.034) *aic: 1505.52*
TWA CLI			
Linear	***1.073 (1.021 – 1.128)*** *aic: 5241.52*	**1.046 (0.968 – 1.131)** *aic: 2617.05*	1.084 (0.986 – 1.191) *aic: 1506.19*
Spline	**≤5.5: 1.146 (1.067 – 1.230)** >5.5: 0.885 (0.740 – 1.057) *aic: 5237.07*	**≤4.9: 1.175 (1.105 – 1.322)** >4.9: 0.770 (0.573 – 1.035) *aic: 2611.538*	**≤3.9: 1.256 (1.064 – 1.483)** >3.9: 0.877 (0.680 – 1.133) *aic: 1503.46*

- Models adjusted for age, gender, BMI, and prior history of LBP

Among the linear spline models, by comparison of AIC scores, TWA CLI performs better for LBP and LT-LBP, and CULI preforms better for SC-LBP. Upon closer examination it can be seen that for LBP and LT-LBP, both CULI and TWA CLI have similar rates of increased risk; about 1.15 and about 1.26, for LBP and LT-LBP, respectively. Whereas for SC-LBP, the CULI both performs better from an AIC score perspective, and has a stronger effect size with a 1.36 versus 1.18 per unit rate of increase. Taken as a whole, this suggests that, of the two

approaches, CULI is more useful for quantifying and designing physical exposures from daily lifting and lowering with job rotation (Table 15).

2.4.3 Exposure-Response for Lift/Lower Parameters

Over the decades, several studies have investigated lifting parameters such as weight lifted, twisting while lifting, and bending while lifting as independent risk factors for LBP. Results of these studies have been inconclusive with regard to increased risk of LBP with few prospective studies and no prospective studies that have specifically aimed to study these factors with detailed quantification. In addition to the scientific curiosity and uncertainty, these independent lifting factors are important to study and quantify because they can be very easily translated into practical guidelines and policy for a variety of industries and are also very easily surveilled in nearly all working environments.

2.4.3.1 Analyses of Individual Lift/Lower Parameters

For this study, five independent parameters of lifting were studied by isolating RNLE variables and taking their maximum (or minimum where appropriate) values across all lifts/lowers and all tasks performed. These measures were: (1) peak weight lifted in lbs, (2) peak asymmetric angle, which serves as a proxy for "twisting" of the trunk while lifting, (3) peak horizontal location of the hands in inches, which serves as a proxy for reaching while lifting, (4) minimum vertical location of the hands, which serves as a proxy for bending while lifting, and (5) total lifting frequency across all tasks performed, expressed as average lifts per minute for a shift.

To study these variables, both simple linear and linear spline models were built for each variable and incidence for each outcome (15 total models). All models were a-priori adjusted for age, gender, BMI, and lifetime history of LBP. AIC score was used to compare model performance within outcome. Results are presented in Table 16.

Peak weight, peak twisting, peak reaching, and peak bending all showed association with LBP, SC-LBP, and LT-LBP. Total average frequency was associated with LBP and SC-LBP but not with LT-LBP. In general, and consistent with RNLE exposure results, linear spline models showed stronger associations because the splines could account for non-linearities that occurred above certain high-exposure thresholds.

For peak weight, risk increased by between 1.7 and 2.4% per lb up to between 42 and 53 lbs, after which risk began to decrease (for LBP and SC-LBP) or stayed level (for LT-LBP. This translate**d** to peak HRs of 2.3, 2.4 and 2.9 for LBP, SC-LBP, and LT-LBP, respectively. By AIC score, peak weight was the most predictive of the independent parameters for incidence of LBP (Table 16).

For peak twisting, simple linear models were associated with increased risk of SC-LBP and LT-LBP, with rates of increase of 0.9% and 1.1% per degree. However, linear spline models showed stronger associations and lower AIC scores than the simple linear models. For the spline models, **peak** twisting was associated with all three outcomes with rates of increase between 0.7 and 1.8% per degree of twisting up to between 73 and 83 degrees of trunk rotation. Beyond the knots risk was level, or in the case of SC-LBP risk began to statistically decrease. Peak HRs were 1.7, 3.7, and 4.3 for LBP, SC-LBP, and LT-LBP, respectively. By AIC score, peak twisting was the second best predictor of incidence of SC-LBP and LT-LBP.

Table 16: Incident Analyses of Peak Lifting Parameters

Factor	LBP	SC-LBP	LT-LBP
Peak Weight (W)			
Linear	1.000 (0.996 – 1.005)	1.004 (0.998 – 1.009)	1.005 (0.997 – 1.012)
	aic: 5248.729	*aic: 2616.84*	*aic: 1507.37*
Spline	**≤42: 1.020 (1.010 – 1.030)**	**≤53: 1.017 (1.007 – 1.027)**	**≤45: 1.024 (1.007 – 1.041)**
	>42: 0.983 (0.974 – 0.992)	**>53: 0.980 (0.964 – 0.997)**	>45: 0.986 (0.970 – 1.003)
	aic: 5229.27	*aic: 2608.90*	*aic: 1502.64*
Peak Twisting (A)			
Linear	1.002 (0.999 – 1.005)	**1.009 (1.004 – 1.013)**	**1.011 (1.005 – 1.016)**
	aic: 5247.76	*aic: 2603.50*	*aic: 1494.96*
Spline	**≤73: 1.007 (1.002 – 1.011)**	**≤83: 1.016 (1.011 – 1.022)**	**≤82: 1.018 (1.010 – 1.026)**
	>73: 0.988 (0.976 – 0.999)	**>83: 0.978 (0.955 – 0.997)**	>82: 0.990 (0.972 – 1.010)
	aic: 5242.71	*aic: 2591.391*	*aic: 1490.84*
Peak Reach (H)			
Linear	**1.037 (1.018 – 1.056)**	**1.091 (1.061 – 1.121)**	**1.088 (1.051 – 1.127)**
	aic: 5234.03	*aic: 2577.72*	*aic: 1484.76*
Spline	≤31: 1.012 (0.985 – 1.041)	**≤30: 1.055 (1.010 – 1.102)**	≤30: 1.027 (0.973 – 1.085)
	>31: 1.075 (1.009 – 1.145)	**>30: 1.149 (1.082 – 1.220)**	**>30: 1.182 (1.099 – 1.272)**
	aic: 5231.24	*aic: 2576.307*	*aic: 1480.82*
Peak Bend (V)			
Linear	0.993 (0.984 – 1.002)	**0.986 (0.973 – 0.999)**	**0.987 (0.970 – 1.004)**
	aic: 5246.15	*aic: 2613.52*	*aic: 1506.35*
Spline	**≤25: 0.984 (0.970 – 0.998)**	**≤12: 1.067 (1.005 – 1.124)**	**≤11: 1.123 (1.032 – 1.223)**
	>25: 1.015 (0.987 – 1.044)	**>12: 0.965 (0.946 – 0.985)**	**>11: 0.959 (0.935 – 0.984)**
	aic: 5245.705	*aic: 2607.74*	*aic: 1497.95*
Frequency (F)			
Linear	**1.072 (1.026 – 1.120)**	**1.048 (0.981 – 1.120)**	0.988 (0.893 – 1.094)
	aic: 5239.99	*aic: 2616.47*	*aic: 1508.70*
Spline	**≤4.1: 1.129 (1.044 – 1.223)**	**≤5.7: 1.149 (1.046 – 1.262)**	≤5.6: 1.015 (0.893 – 1.153)
	>4.1: 1.003 (0.907 – 1.109)	>5.7: 0.726 (0.505 – 1.044)	>5.6: 0.868 (0.561 – 1.342)
	aic: 5239.53	*aic: 2610.763*	*aic: 1510.234*

For peak reach distance, simple linear models were predictive of increased risk of all three LBP outcomes with rates of increase between 3.7% and 9.1% per inch of reach. By AIC score comparison, linear splines performed better, but for all models the relationship showed a relatively shallow increase in risk up to the knots of 30 to 31 inches followed but a sharp and statistically significant increase in risk of between 7.5% and 18.2% per inch of reach. Given this, and given how well the simple linear models perform, it seems more practical to use the simple linear models. At 30 inches of horizontal reach and using the simple linear models, HRs are 3.0, 13.6, and 12.6 for LBP, SC-LBP and LT-LBP respectively. Even accounting for a practical minimum of 8 inches of horizontal reach for any lift/lower, HRs at 30 inches (relative to 8") are 2.2, 6.8, and 6.4 for LBP, SC-LBP and LT-LBP, respectively. By AIC score, peak reach is the strongest predictor of SC-LBP and LT-LBP and the second strongest predictor of LBP.

For peak bending, simple linear models were associated with SC-LBP and LT-LBP, but not with LBP. Linear spline models were associated with all three outcomes. Because the reference point is floor level, increasing height in inches represented less presumed bending and was thus protective at rates between 1.4% and 4.1% decrease in risk per inch of increased vertical location. Similar to peak reach, it is more practical to use simple linear models to describe the risk and while that can be done for the outcomes of SC-LBP and LT-LBP, it cannot easily be done for LBP due to a non-linearity in the exposure response when vertical location exceeds 25 inches from the floor. Nonetheless, if we use the first leg of the linear spline for LBP and then the simple linear models for SC-LBP and LT-LBP, then the HRs at floor level, relative to 25" from floor level (i.e., just below typical waist height) are 1.5, 1.4 and 1.4, respectively.

For frequency, both linear and linear spline models were associated with increased risk of LBP and SC-LBP, and neither were associated with LT-LBP. For LBP, linear and linear spline models had similar AIC scores. For SC-LBP, the AIC score for the linear spline was markedly lower. For both outcomes, risk increased up to the knot and then statistically leveled. Rate of increase was 12.9% and 14.9% per lift per minute of frequency up to knots of 4.1 and 5.7 for LBP and SC-LBP, respectively. These produced peak HRs of 1.6 and 2.2 for LBP and SC-LBP respectively.

Summary of Independent Lift/Lower Parameters and Primary Risk Factors

Contrary to recent systematic reviews that have suggested that biomechanical factors do not appear to be independent risk factors for LBP, these results suggest that not only are biomechanical risk factors independent risk factors, but also that they are potentially strong ones. HRs for these simple, independent factors are comparable to, or greatly exceed those of the RNLE measures. This suggests that peak exposures have an outsized influence on risk for LBP, SC-LBP, and LT-LBP among all physical exposure to a worker.

2.4.3.2 Interactions Between Individual Lift/Lower Parameters

Based on the strength of the results for the independent parameters, simple interactive models were created between load (i.e., peak weight) and the other factors, and between peak twisting and the other factors. In addition, a combination of bending (i.e., vertical location) and frequency was examined. For all scenarios, parameters were split at their medians and then combined into four groups where both were below their medians, both were above their medians, and two categories where one or the other were above their medians. Combinations with peak load are reported in Table 17 and with peak twisting and bending with frequency are reported in Table 18.

For load-twist combinations, none of the combinations was associated with LBP. For SC-LBP and LT-LBP, peak load above the median alone was not associated, but peak twisting above the median alone was associated with HR of 1.8 for SC-LBP and 3.8 for LT-LBP. For peak load and peak twisting together, HRs were markedly higher at 3.4 for SC-LBP and 6.7 for LT-LBP. Thus, for LBP and SC-LBP, peak weight and peak twisting did not seem to be interacting with one another (i.e., no association, or association comparable to independent factor models), but for LT-LBP there appears to be an interaction between peak load and peak twisting (i.e., HR is increased well beyond the independent factor alone. By AIC score comparison, combinations of load and twisting are the best predictors of SC-LBP and LT-LBP from among the combination models. For SC-LBP the combination of load and twisting has comparable AIC to twisting alone, whereas for LT-LBP the combination model has much lower AIC than twisting alone.

For load and reach, there was at least some association with all three outcomes, but the association with LBP was weak and confined to only the combination of high reach and high load. For SC-LBP and LT-LBP, load only showed no effect whereas reach only showed HRs of 1.5 and 1.9 for SC-LBP and LT-LBP, respectively, and increased to 2.1 and 2.4 for SC-LBP and LT-LBP, respectively when both reach and load were high. However, it should be noted that AIC values for all these models are higher than for models with reach alone. A scheme to analyze load-moment across the wide variety of tasks and subtasks that workers perform would be needed to further study this potentially important interaction between reach and load.

Table 17: Incident Analyses of Interactions Among Peak Lifting Parameters and Peak Load

Factor	LBP	SC-LBP	LT-LBP
Load-Twist			
Low, Low	1.00	1.00	1.00
Load Only	1.06 (0.86 – 1.30)	1.10 (0.80 – 1.51)	1.15 (0.72 – 1.82)
Twist Only	1.17 (0.84 – 1.64)	**1.78 (1.10 – 2.87)**	**3.79 (2.13 – 6.75)**
Load+Twist	1.42 (0.96 – 2.11)	**3.37 (2.02 – 5.59)**	**6.66 (3.60 – 12.31)**
	aic: 5261.55	*aic: 2591.26*	*aic: 1473.38*
Load-Reach			
Low, Low	1.00	1.00	1.00
Load Only	0.93 (0.73 – 1.19)	0.95 (0.66 – 1.37)	0.97 (0.57 – 1.63)
Reach Only	1.29 (0.95 – 1.74)	**1.54 (1.00 – 2.37)**	**1.93 (1.13 – 3.31)**
Load+Reach	**1.50 (1.16 – 1.95)**	**2.06 (1.45 – 2.93)**	**2.44 (1.54 – 3.86)**
	aic: 5252.40	*aic: 2592.68*	*aic: 1495.04*
Load-Bend			
Low, Low	1.00	1.00	1.00
Load Only	0.94 (0.70 – 1.26)	1.23 (0.83 – 1.82)	1.21 (0.70 – 2.10)
Bend Only	1.09 (0.85 – 1.39)	1.06 (0.73 – 1.53)	1.14 (0.69 – 1.88)
Load + Bend	1.22 (0.97 – 1.54)	1.29 (0.92 – 1.81)	1.48 (0.96 – 2.29)
	aic: 5260.73	*aic: 2608.81*	*aic: 1509.53*
Load-Frequency			
Low, Low	1.00	1.00	1.00
Load Only	0.92 (0.71 – 1.21)	0.93 (0.64 – 1.37)	1.09 (0.68 – 1.74)
Hi Freq Only	1.20 (0.94 – 1.53)	0.99 (0.69 – 1.43)	0.68 (0.41 – 1.15)
Load+Hi Freq	**1.42 (1.11 – 1.82)**	**1.61 (1.14 – 2.27)**	1.26 (0.79 – 2.01)
	aic: 5253.75	*aic: 2602.08*	*aic: 1507.86*

- All models adjusted for age, gender, BMI, and prior history of LBP

For load and bend, and load and frequency there were no apparent associations with any of the three outcomes.

For twist and reach (Table 18) there was at least some association with all three outcomes, but similar to load and reach, the association with LBP was weak and confined only to the combination of high twist and high reach. For SC-LBP, the parameters were significant when isolated and had increased HR of 4.7 when combined. For LT-LBP, reach only was not significant but show an elevated HR. Twist only was significant and the combination of twist and reach had HR of 8.6 – perhaps suggesting an important interaction between twisting and reaching. AIC scores for these models were the same or lower than for models with reaching alone. However, it should be noted that HRs were lower than from models with reaching as the lone independent physical exposure factor.

For combinations of twisting and frequency, associations were found for all three outcomes. However, for LBP the combination category was not significant. For SC-LBP and LT-LBP the high frequency only category was not significant and the combination category had lower HRs than twist only. Nonetheless, the AIC score for the twisting and frequency model with LT-LBP outcome was lower than the model for twisting alone or frequency alone suggesting some relevance between these factors, at least for the data from this cohort.

Bending (i.e, vertical location) and frequency showed no association with SC-LBP or LT-LBP and association with LBP was confined to only the combination category and the HR was relatively low at 1.5.

Table 18: Incident Analyses of Interactions Among Peak Lifting Parameters and Peak Twisting, and Interaction Between Bending and Lifting Frequency

Factor	LBP	SC-LBP	LT-LBP
Twist-Reach			
Low, Low	1.00	1.00	1.00
Reach Only	1.22 (0.96 – 1.56)	**1.53 (1.05 – 2.22)**	1.44 (0.85 – 2.42)
Twist Only	0.90 (0.61 – 1.31)	**1.77 (1.03 – 3.01)**	**2.83 (1.49 – 5.35)**
Twist+Reach	**1.98 (1.38 – 2.83)**	**4.67 (2.97 – 7.32)**	**8.62 (4.78 – 15.55)**
	aic: 5236.22	*aic: 2580.34*	*aic: 1463.95*
Twist-Bend			
Low, Low	1.00	1.00	1.00
Bend Only	1.16 (0.95 – 1.42)	1.23 (0.89 – 1.71)	1.06 (0.68 – 1.67)
Twist Only	1.24 (0.89 – 1.73)	**2.81 (1.74 – 4.52)**	**3.46 (1.91 – 6.26)**
Twist+Bend	**1.50 (1.00 – 2.26)**	**3.07 (1.83 – 5.16)**	**7.01 (3.77 – 13.06)**
	aic: 5247.75	*aic: 2594.317*	*aic: 1472.24*
Twist-Frequency			
Low, Low	1.00	1.00	1.00
Hi Freq Only	**1.40 (1.13 – 1.73)**	1.31 (0.95 – 1.80)	0.95 (0.59 – 1.54)
Twist Only	**1.52 (1.06 – 2.19)**	**2.94 (1.86 – 4.66)**	**5.23 (2.96 – 9.24)**
Twist+Hi Freq	1.38 (0.97 – 1.98)	**1.88 (1.82 – 4.56)**	**3.60 (1.98 – 6.54)**
	aic: 5240.40	*aic: 2593.433*	*aic: 1475.86*
Bend-Frequency			
Low, Low	1.00	1.00	1.00
Bend Only	0.91 (0.71 – 1.17)	0.99 (0.69 – 1.42)	1.10 (0.70 – 1.72)
Freq Only	1.01 (0.78 – 1.31)	1.14 (0.79 – 1.64)	0.75 (0.45 – 1.26)
Bend+Hi Freq	**1.54 (1.20 – 1.97)**	1.43 (0.98 – 2.07)	1.17 (0.72 – 1.91)
	aic: 5235.80	*aic: 2618.11*	*aic: 1509.91*

- All models adjusted for age, gender, BMI, and prior history of LBP

2.5 Practical Implications

This study and the independently conducted studies that underly it were designed with the aim of quantifying associations between occupational physical exposures and outcomes of LBP. None of the studies had primary aims to quantify associations with individual, or psychosocial variables. Thus, physical exposure samples, while fundamentally samples of convenience, were nonetheless relatively well balanced with regard to exposure distribution and this overall distribution was improved by combining all the studies. All other factors included in the study were purely convenience samples and so while some potentially important associations were found for factors such as supervisor support, it is not clear that those results are generalizable to the field. Similarly, though the study is well powered, negative findings for individual and psychosocial factors should not be interpreted as providing evidence of no effect in general, but rather as stating that those factors had no effect among these workers.

For translation to field practice there are a few primary aspects to consider: (1) are the findings useful for surveillance, (2) are the findings useful for design and/or intervention, and (3) are the tools needed to implement the findings readily available and simple to use. In these regards this study has potentially very important results.

From a health and safety surveillance perspective the findings that simple measures such as peak weight, peak reach, and peak twisting are strong predictors of LBP outcomes is very positive. These parameters are very easy to quantify and monitor. Further, regular monitoring in a given industry can create internal data that could potentially be used to implement company-wide policies (e.g., reduce the weight of kits/bins in a manufacturing facility to not more than 35lbs). Similarly, the fact that pkFILI works as well as CULI for incidence analyses could dramatically simply what is needed for semi-comprehensive surveillance of complex working

environments. Workers and supervisors could be surveyed to determine which tasks are perceived to be most biomechanically difficult and those tasks could be quantified using the FILI. Because the FILI incorporates several factors (albeit without frequency) and results in a consistent numerical score, the resulting information could be used to help prioritize jobs for further investigation and/or intervention.

From a job design standpoint, validation of the RNLE and in particular all aspects of its measures – FILI, CLI, and CULI – is comforting. The RNLE has proven remarkably flexible and able to be used to analyze and design everything from simple tasks to complex multi-task jobs. While this study suggests that there are potentially meaningful differences between how well the different measures perform with regard to risk prediction, they nonetheless provide stable and consistent measures of exposure that are directly and predictably related to one another. These later attributes are critical for any engineering or design tool to be used over long periods and especially in any industry that relies on a continuous improvement approach to processes.

Lastly the RNLE is freely available and though it does require some training to use properly, the tools is not inherently difficult to understand and does not require intense knowledge of biomechanics or physiology to use. In this regard, companies of all sizes can implement the RNLE in all manner of ways ranging from simple pencil and paper analyses for small companies to customized software and instrument assisted data collection for large organizations.

An important confirmation of this study is the consistent and strong presence of prior history of LBP. This finding is not new. However, in the context of well-measured biomechanical factors these results should help to emphasize the critical importance of preventing or at least substantially delaying first onset of prolonged LBP.

2.6 Conclusion

The RNLE pkFILI, pkCLI, and CULI were consistently associated with prevalence and incidence of LBP, SC-LBP, and LT-LBP. Peak task exposure (pkCLI) was most strongly associated with prevalence and peak sub-task exposure (pkFILI) was most strongly associated with incidence. CULI effectively comparable to pkFILI for predicting risk of incidence of LBP outcomes which might be useful when considering tools to use for new job design.

Peak parameters of lifting/lowering such as peak weight, peak reaching and peak twisting were consistently and strongly associated with incidence of all three LBP outcomes. These measures are simple to surveil and thus could be useful factors to regularly monitor in work settings.

Increased age was associated with prevalence of LBP but not SC-LBP or LT-LBP. Conversely, increased age was protective for incidence of LBP. Gender and BMI were not associated. Psychosocial factors such as coworker support and job satisfaction were associated with prevalence of all three outcomes but not incidence. Lifetime history of LBP was associated with prevalence and incidence outcomes. In prevalence analyses LBP history appeared to confound the effects of physical exposure and reduced the ORs of the RNLE measures by 40 to 50%. Psychosocial factors deserve further investigation as their consistent association with prevalence suggests that studies constructed with the primary aim of quantifying risk of LBP and associated outcomes due to psychosocial strains might reveal important associations that this study could not.

Overall, evidence is provided that biomechanical exposures are independent risk factors for LBP and related outcomes. The findings of this study should help inform future research and intervention strategies. Continuous exposure-response relationships provide a basis for

companies to develop exposure policies. The RNLE provides a foundation for detailed job design, evaluation, and decision making. Associations with individual parameters of lifts/lowers provide a basis for simple surveillance strategies.

2.7 References

1. World Health Organization. (2003). The burden of musculoskeletal conditions at the start of the new millennium. i-x. World Health Organ Tech Report, 919, 1-218. PMID: 14679827.

2. Bigos, S., Bowyer, O., & Braen, G. (1994). Acute low back problems in adults. Clinical practice guidelines no.14. AHCRP publication no. 95-0642 Rockville, MD: Agency for health Care Policy and research, PHS, US DHHS.

3. Waddell, G. & Burton, A. K. (2001). Occupational health guidelines for the management of low back pain at work: evidence review. Occup. Med., 51(2), 124-135. PMID: 11307688. doi: 10.1093/occmed/51.2.124.

4. Walker, B. F., Muller, R., & Grant, W. D. (2004). Low back pain in Australian adults. Health provider utilization and care seeking. J. Manipulative & Physiological Therapeutics, 27(4), 327-335. PMID: 15195040.

5. Bureau of Labor Statistics. (2011). Nonfatal occupational injuries and illnesses requiring days away from work, 2010. Bureau of Labor Statistics, U.S. Department of Labor. USDL-11-1612. www.bls.gov/iif/oshcdnew.htm. PMCID: PMC1765409.

6. Dunning, K. K., Davis, K. G., Cook, C., Kotowski, S. E., Hamrick, C., Jewell, G., & Lockey, J. (2010). Costs by industry and diagnosis among musculoskeletal claims in a state workers compensation system: 1999-2004. Am J Ind Med, 53, 276-284. PMID: 19937981.

7. Washington Department of Labor & Industries. (2011). Injury data, L&I Workers' Compensation Claims: Body Part Injured. www.lni.wa.gov/ClaimsIns/Insurance/dataStatistics/WorkersCompdata/default.asp.

8. Manchikanti, L. (2000). Epidemioloy of low back pain. Pain Physician, 3(2), 167-192. PMID: 16906196.

9. Garg, A., Boda, S., Hegmann, K. T., Moore, J. S., Kapellusch, J. M., Bhoyar, P., Thiese, M.S., Merryweather, A., Deckow-Schaefer, G., Boswick, D., & Malloy, E. J. (2014). The NIOSH Lifting Equation and Low-Back Pain, Part 1 Association With Low-Back Pain in the BackWorks Prospective Cohort Study. Human Factors, 56(1), 6-28. PMID: 24669540.

10. Hayden, J. A., Chou, R., Hogg-Johnson, S., & Bombardier, C. (2009). Systematic reviews of low back pain prognosis had variable methods and results-guidance for future prognosis reviews. J Clinical Epidemiology, 62, 781-796. PMID: 19136234.

11. Hartvigsen, J., Bakketeig, L. S., Leboeuf-Yde, C., Engberg, M., & Lauritzen, T. (2001). The association between physical workload and low back pain clouded by the "healthy worker" effect: population-based cross-sectional and 5-year prospective questionnaire study. Spine, 26(16), 1788. PMID: 11493851

12. Ozguler, A., Leclerc, A., Landre, M., Pietri-Taleb, F., & Niedhammer, I. (2000). Individual and occupational determinants of low back pain according to various definitions of low back pain. J Epidemiol Community Health, 54, 215-220. PMID: 10746116.

13. Deyo, R. A., Dworkin, S. F., Amtmann, D., Andersson, G., Borenstein, D., Carragee, E., Carrino, J., Chou, R., Cook, K., DeLitto, A., Goertz, C., Khalsa, P., Loeser, J., Mackey, S. Panagis, J., Rainville, J., Tosteson, T., Turk, D., Von Korff, M., & Weiner, D. K. (2014). Report of the NIH Task Force on Research Standards for Chronic Low Back Pain. The Journal of Pain, 15(6), 569-585. PMID: 24787228.

14. Garg, A., Kapellusch, J. M., Hegmann, K. T., Moore, J. S., Boda, S., Bhoyar, P., Thiese, M.S., Merryweather, A., Deckow-Schaefer, G., Bloswick, D., & Malloy, E. J. (2014). The NIOSH Lifting Equation and Low-Back Pain, Part 2 Association With Seeking Care in the BackWorks Prospective Cohort Study. Human Factors: The Journal of the Human Factors and Ergonomics Society, 56(1), 44-57. PMID: 24669542.

15. Kapellusch, J. M., Garg, A., Boda, S., Hegmann, K. T., Moore, J. S., Thiese, M. S., Merryweather, A., Tomich, S., Foster, J.C., Bloswick, D., & Malloy, E. J. (2014). Association Between Lifting and Use of Medication for Low Back Pain: Results From the Backworks Prospective Cohort Study. Journal of Occupational and Environmental Medicine, 56(8), 867-877. doi: 10.1097/JOM.0000000000000197.

16. Ferguson, S. A., & Marras, W. S. (1997). A literature review of low back disorder surveillance measures and risk factors. Clinical Biomechanics, 12(4), 211-226. PMID: 11415726.

17. Dagenais, S., Caro, J., & Haldeman, S. (2008). A systematic review of low back pain cost of illness studies in the United States and internationally. The Spine Journal, 8(1), 8-20. PMID: 18164449.

18. Chaffin, D.B., & Park, K.S. (1973). A longitudinal study of low back pain as associated with occupational lifting factors. Am. Ind. Hyg. Assoc. J, 34, 513-525. PMID: 4272346.

19. Garg, A., & Chaffin, D. B. (1975). A biomechanical computerized simulation of human strength. AIIE Transactions, 7, 1-15. DOI:10.1080/05695557508974978.

20. Liles, D. H., & Mahajan, P. (1985). Using NIOSH Lifting Guide decreases risk of back injury. Occup. Health Safety, Feb, 57-60. PMID: 3982769.

21. Herrin, G. D., Jaraiedi, M., & Anderson, C. K. (1986). Prediction of over- exertion injuries using biomechanical and psychophysical models. Amer Indus Hyg Assoc J, 47(6), 322-330. PMID: 2943150.

22. Marras, W. S., Lavender, S. A., Leurgans, S. E., Rajulu, S. L., Allread, W. G., Fathallah, F. A., & Ferguson, S. A. (1993). The role of dynamic three-dimensional trunk motion in occupationally related low back disorders. Spine, 18(5), 617-628. PMID: 8484154.

23. Norman, R., Wells, R., Neumann, P., Frank, J., Shannon, H., & Kerr, M. (1998). A comparison of peak vs. cumulative physical work exposure risk factors for the reporting of low back pain in the automotive industry. Clin Biomech (Bristol,Avon), 13(8), 561-573. PMID: 11415835.

24. Hoogendoorn, W. E., Bongers, P. M., de Vet, H. C. W., Douwes, M., Koes, B. W., Miedema, M. C., Ariens, G. A., & Bouter, L. M. (2000). Flexion and rotation of the trunk and lifting at work are risk factors for low back pain: results of a prospective cohort study. Spine, 25(23),

3087-3092. PMID:11145822.

25. Kerr, M.S., Frank, .W., Shannon, H.S., Norman, R.W.K., Wells, R.P., Neumann, W.P., Bombardier, C., & the Ontario Universities Back Pain Study Group. (2001). Biomechanical and psychosocial risk factors for low back pain at work. Amer. J. Public Health, 91(7), 1069-1075. PMID: 11441733.

26. Tubach, F., Leclerc, A., Landre, M., & Pietri-Taleb, F. (2002). Risk factors for sick leave due to low back pain: a prospective study. JOEM, 44(5), 451-458. PMID: 12024690.

27. Hoogendoorn, W. E., Bongers, P. M., de Vet, H. C. W., Ariens, G. A., van Mechelen, W., & Bouter, L.M. (2002). High physical work load and low job satisfaction increase the risk of sickness absence due to low back pain: results of a prospective cohort study. Occup Environ Med, 59, 223-328. PMID: 11983847.

28. Hoogendoorn, W. E., Bongers, P. M., de Vet, H. C. W., Twisk, J. W. R., van Mechelen, W., & Bouter, L. M. (2002). Comparison of two different approaches for the analysis of data from a prospective cohort study: an application to work related risk factors for low back pain. Occup Environ Med., 59, 459-465. PMCID: PMC1740320.

29. Harkness , E. F., Mcfarlane, G. J., Nahit, E. S., Silman, A. J., & Mcbeth, J. (2003). Risk factors for new-onset low back pain amongst cohorts of newly employed workers. Rheumatology, 42:959-968. PMID: 12730508.

30. Jansen, J. P., Morgenstern, H., & Burdorf, A. (2004). Dose-response relations between occupational exposure and psychosocial factors and the risk of low back pain. Occup Environ Med, 61, 972-979. PMCID: PMC1740687.

31. Balogh, I., Orbaek, P., Ohlsson, K., Nodander, C., Unge, J., Winkel, J., & Hansson, G. (2004). Self-assessed and directly measured occupational physical activities-influence of musculoskeletal complaints, age and gender. Applied Ergonomics, 35 (1), 49-56. PMID: 14985140.

32. Punnett, L., & Wegman, D.H. (2004). Work-related musculoskeletal disorders: the epidemiologic evidence and the debate. J Electromyography and Kinesiology, 14(1), 13-23. PMID: 14759746.

33. Van Nieuwenhuyse, A., Somville, P.R., Crombez, G., Burdorf, A., Verbeke, G., Johannik, K., van den Bergh, O., Masschelein, R., Mairiaux, P., Moens, G. F., & the BelCoBack Study Group. (2006). The role of physical workload and pain related fear in the development of low back pain in young workers: evidence from the BelCoBack Study; results after one year of follow up. Occup Environ Med, 63, 45-52. PMCID: PMC2078035.

34. Plouvier, S., Leclerc, A., Chastang, J, Bonenfant, S., & Goldberg, M. (2009). Socioeconomic position and low-back pain-the role of biomechanical strains and psychosocial work factors in the GAZEL cohort. Scand J Work Environ Health, 35(6), 429-436. PMID: 19806277.

35. Marras, W.S., Lavender, S.A., Ferguson, S.A., Splittstoesser, R. E., & Yang, G. (2010). Quantitative dynamic measures of physical exposure predict low back functional impairment. Spine, 35(8), 914-923. PMID: 20354470.

36. Waters, T. R., Lu, M., Piacitelli L. A., Werren, D., & Deddens, J. A. (2011). Efficacy of the revised NIOSH lifting equation to predict low back pain due to manual lifting. Expanded cross- sectional analysis. Journal of Occupational and Environmental Medicine, 53(9), 1061-1067. PMID: 21866048.

37. Matsudaira, K., Konishi, H., Miyoshi, K., Isomura, T., Takeshita, K., Hara, N., Yamada, K., & Machida, H. (2012). Potential risk factors for new onset of back pain disability in Japanese workers: findings from the Japan epidemiological research of occupation-related back pain study. Spine, 37(15), 1324-1333. PMID: 22246538.

38. Vandergrift, J. L., Gold J. E., Hanlon, A., & Punnett, L. (2012). Physical and psychosocial ergonomic risk factors for low back pain in automobile manufacturing workers. Occup Environ Med, 69, 29-34. PMID: 21586759.

39. Lu, M. L., Waters, T. R., Krieg, E., & Werren, D. (2014). Efficacy of the Revised NIOSH Lifting Equation to Predict Risk of Low-Back Pain Associated With Manual Lifting A One-Year Prospective Study. Human Factors, 56(1), 73-85. PMID: 24669544.

40. Bakker, E. W. P., Verhagen, A. P., van Trijffel, E., Lucas, C., & Koes, B. W. (2009). Spinal mechanical load as a risk factor for low back pain: a systematic review of prospective cohort studies. Spine, 34 (8), 281-293. PMID: 19365237.

41. Roffey, D. M., Wai, E. K., Bishop, P., Kwon, B. K., & Dagenais, S. (2010a). Causal assessment of awkward occupational postures and low back pain: results of a systematic review. Spine J, 10, 89–99. doi:10.1016/j.spinee.2009.09.003.

42. Balagué, F., Mannion, A. F., Pellisé, F., & Cedraschi, C. (2012). Non-specific low back pain. Lancet, 379, 482–91. doi:10.1016/S0140-6736(11)60610-7.

43. Punnet L., Fine, L.J., Keyserling, W.M., Herrin, G.D., & Chaffin, D.B. (1991). Back disorders and nonneutral trunk postures of automotive assembly workers. Scandinavian J. Work, Environment and Health, 17:337-346. PMID: 1835131.

44. Waddell, G. & Burton, A. K. (2001). Occupational health guidelines for the management of low back pain at work: evidence review. Occup. Med., 51(2), 124-135. PMID: 11307688.

45. van der Molen, H.F., Sluiter, J.K., Hulshof, C.T.J., Vink, P., & Frings-Dresen, M.H.W. (2005). Effectiveness of measures and implementation strategies in reducing physical work demands due to manual handling at work. Scand J Work Environ Health, 31 suppl 2:75-87. PMID: 16363450.

46. Nelson, N. A., & Hughes, R. E. (2009). Quantifying relationships between selected work-related risk factors and back pain: a systematic review of objective biomechanical measures and cost-related health outcomes. Int J Ind Ergon, 39(1), 202-210. PMCID: PMC2662685.

47. Snook, S.H. & Ciriello, V.M. (1991). The design of manual handling tasks: revised tables of maximum acceptable weights and forces. Ergonomics, 34 (9), 1197-1213. PMID: 1743178.

48. Marras, W. S., Fine, L. J., Ferguson, S. A., & Waters, T. R. (1999). The effectiveness of commonly used lifting assessment methods to identify industrial jobs associated with elevated risk of low-back disorders. Ergonomics, 42(1), 229-245. PMID: 9973881.

49. Waters, T. R., Baron S. L., Piacitelli L. A., Anderson V. P., Skov T., Haring-Sweeney M., Wall D. K., & Fine L. J. (1999). Evaluation of the revised NIOSH lifting equation. A cross-sectional epidemiologic study. Spine, 24(4), 386-395. PMID: 10065524.

50. Waters, T.R., Putz-Anderson, V., & Baron, S. (1998). Methods for assessing physical demands of manual lifting: a review and case study from warehousing. Amer. Indus. Hyg. Assoc. J., 59, 871-881. PMID: 9866167.

51. Waters, T. R., Putz-Anderson, V., Garg, A., & Fine, L. J. (1993). Revised NIOSH equation for the design and evaluation of manual lifting tasks. Ergonomics, 36(7), 749-776. PMID: 8339717.

52. Waters, T.R., Putz-Anderson, V., Garg, A., & Fine, L. J. (1994). Applications manual for the revised NIOSH lifting equation. U.S. Department of Health and Human Services (Pub. No. 94- 110). Cincinnati, OH: DHHS (NIOSH).

53. Garg, A., Chaffin, D. B., & Herrin, G. D. (1978). Prediction of metabolic rates for manual materials handling jobs. The American Industrial Hygiene Association Journal, 39(8), 661-674. PMID: 696629.

54. Mirka, G. A., Kelaher, D. P., Nay, D. T., & Lawrence, B. M. (2000). Continuous assessment of back stress (CABS): a new method to quantify low-back stress in jobs with variable biomechanical demands. Human Factors, 42(2), 209-225. PMID: 11022881.

55. Van der Beek, A. J., Mathiassen, S. E., Windhorst, J., & Burdorf, A. (2005). An evaluation of methods assessing the physical demands of manual lifting in scaffolding. Applied Ergonomics, 36, 213-222. PMID: 15694076.

56. Russell, S. J., Winnemuller, L., Camp, J. E., & Johnson, P. W. (2007). Comparing the results of five lifting analysis tools. Applied Ergonomics, 38, 91-97. PMID: 16867298.

57. Kucera, K. L., Loomis, D., Lipscomb, H. J., Marshall, S. W., Mirka, G., & Daniels, J. (2009). Ergonomic risk factors for low back pain in North Carolina crab pot and gill net commercial fishermen. Am J Ind Med, 52(4), 311-321. PMCID: PMC2756989.

58. Boda, S., Garg, A., & Campbell-Kyureghyan, N. (2012). Can the Revised NIOSH Lifting Equation Predict Low Back Pain Incidence in a '90-day-pain-free-cohort'? Proceedings of HFES, Boston, 1178-1182.

59. Wang, M. J. J., Garg, A., Chang, Y. C., Shih, Y. C., Yeh, W. Y., & Lee, C. L. (1998). The relationship between low back discomfort ratings and the NIOSH lifting index. Human Factors: The Journal of the Human Factors and Ergonomics Society, 40(3), 509-515. PMID: 9849108.

60. Chung, M. K., & Kee, D. (2000). Evaluation of lifting tasks frequently performed during fire brick manufacturing processes using NIOSH lifting equations. International Journal of Industrial Ergonomics, 25(4), 423-433.

61. Dempsey, P. G., McGorry, R. W., & Maynard, W. S. (2005). A survey of tools and methods used by certified professional ergonomists. Applied Ergonomics, 36(4), 489-503. PMID: 15892943.

62. Kuijer, P. P. F., Verbeek, J. H., Visser, B., Elders, L. A., Van Roden, N., Van den Wittenboer, M. E., Lebbink, M., Burdorf, A., & Hulshof, C. T. (2014). An Evidence-Based Multidisciplinary Practice Guideline to Reduce the Workload due to Lifting for Preventing Work-Related Low Back Pain. Annals of Occupational and Environmental Medicine, 26, 16. PMCID: PMC4081511.

63. Garg, A., & Kapellusch, J. M. (2016). The cumulative lifting index (CULI) for the revised NIOSH lifting equation: quantifying risk for workers with job rotation. Human Factors, 58(5), 683-694. PMID: 26896406

64. Padula, R. S., Comper, M. L. C., Sparer, E. H., & Dennerlein, J. T. (2017). Job rotation designed to prevent musculoskeletal disorders and control risk in manufacturing industries: A systematic review. Applied ergonomics, 58, 386-397. PMID: 27633235

65. Weston, E. B., Aurand, A. M., Dufour, J. S., Knapik, G. G., & Marras, W. S. (2020). One versus two-handed lifting and lowering: lumbar spine loads and recommended one-handed limits protecting the lower back. Ergonomics, 63(4), 505-521. PMID: 32024437

66. Deyo, R., & Tsui-Wu, Y. (1987). Descriptive epidemiology of low-back pain and its related medical care in the United States. Spine, 12(3), 264-268. PMID: 2954221.

67. Papageorgiou, A., Croft, P., Ferry, S., Jayson, M., & Silman, A. (1995). Estimating the prevalence of low back pain in the general population – evidence from the South Manchester back pain survey. Spine, 20(17), 1889-1894. PMID: 8560337.

68. Riihimaki, H. (2000). Epidemiology of work-related back disorders. In: Occupational ergonomics: Work related musculoskeletal disorders of the upper limb and back. F. Violanre, T. Armstrong and A. Kilbom (eds). NY: Taylor & Francis.

69. Kopec, J.A., Sayre,E.C., & Estdaile, J.M. (2004). Predictors of back pain in a general population cohort. Spine, 29 (1), 70-77. PMID: 14699279.

70. Walker, BF, Muller, R., & Grant, WD. (2004). Low back pain in Australian adults. Prevalence and associated disability. J Manipulative & Physiological Therapeutics, 27(4), 238-244. PMID: 15148462.

71. Cote, P., Baldwin, M. L. & Johnson, W. G. (2005). Early patterns of care for occupational back pain. Spine, 30(5), 581-587. PMID: 15738794.

72. IJzelenberg, W & Burdorf, A. (2005). Risk factors for musculoskeletal symptoms and ensuing healthcare use and sick leave. Spine, 30(13), 1550-1556. PMID: 15990672.

73. Leboeuf-Yde, C. (2000). Body weight and low back pain: a systematic literature review of 56 journal articles reporting on 65 epidemiologic studies. Spine, 25(2), 226. PMID: 10685488.

74. Shiri, R., Karppinen, J., Leini-Arhas, P., Solovieva, S., & Viikari-Juntura, E. (2009). The association between obesity and low back pain: a meta-analysis. Amer. J. Epidemiology, 171(2), 135-154. PMID: 20007994.

75. Hincapie, C. A., Cassidy, J. D., & Cote, P. (2008). Is history of work-related low back injury associated with prevalent low back pain and depression in general population. BMC

Musculosketel Disord, 9, 22. PMCID: PMC2277439.

76. Bongers, P. M., De Winter, C., Kompier, M. A. J., & Hildebrandt, V. H. (1993). Psychosocial factors at work and musculoskeletal disease. Scand J Work Environ Health, 19, 297–312. PMID: 8296178.

77. Davis, K.G. & Heaney, C.A. (2000). The relationship between psychosocial work characteristics and low back pain: underlying methodological issues. Clinical Biomechanics, 15(6), 389-406. PMID: 10771118.

78. Marras, W.S., Davis, K.G., Heaney, C.A., Maronitis, A.B. & Allread, W.G. (2000). The influence of psychosocial stress, gender and personality on mechanical loading of the lumbar spine. Spine, 25, 3045 – 3054. PMID: 11145816.

79. Hartvigsen, J., Lings, S., Leboeuf-Yde, & Bakketeig, L. (2004). Psychosocial factors at work in relation to low back pain and consequences of low back pain: a systematic, critical review of prospective cohort studies. Occup Environ Med, 61, e2. PMCID: PMC1757801.

80. Clays, E., De Bacquer, D., Leynen, F., Kornitzer, M., Kittel, F, & De Backer, G. (2007). The impact of psychosocial factors on low back pain: longitudinal results from the Belstress study. Spine, 32(2), 262-268. PMID: 17224824.

81. Ramond, A., Bouton, C., Richard, I., Roquelaure, Y., Baufreton, C., Legrand, E. & Huez, J. (2011). Psychosocial risk factors for chronic low back pain in primary care—a systematic review. Family Practice, 28, 12–21. PMID: 20833704.

82. Hoogendoorn, W. E., van Popel, M. N., Bongers, P. M., Koes, B. W., & Bouter, L. M. (2000). Systematic review of psychosocial factors at work and private life as risk factors for back pain. Spine, 25, 2114-2125. PMID: 10954644.

83. Van Nieuwenhuyse, A., Fathutdinova, L., Verbeke, G., Pirenne, D., Johannik, K., Somville, P. R., Mairiaux, Ph., Moens, G. F., & Masschelein, R. (2004). Risk factors for first-ever low back pain among workers in their first employment. Occupational Medicine, 54, 513-519. PMID: 15385649.

84. Macfarlane, G. J., Pallewate, N., Paudyal, P., Blyth, F. M., Coggon, D., Grombz, G., Linton, S., Leino-Arjas, P., Silman, A. J., Smeets, R. J., & van der Windt, D. (2009). Evaluation of work- related psychosocial factors and regional musculoskeletal pain: results from a EULAR task force. Ann Rheum Dis, 66, 885-891. PMID: 18723563.

85. Thiese, M. S., Lu, M. L., Merryweather, A., Tang, R., Ferguson, S. A., Malloy, E. J., ... & Kapellusch, J. (2020). Psychosocial Factors and Low Back Pain Outcomes in a Pooled Analysis of Low Back Pain Studies. Journal of occupational and environmental medicine, 62(10), 810-815. PMID: 32568818

86. Collett D. 2003. Modeling survival data in medical research. London: Chapman & Hall/CRC.

87. Steenland, K., & Deddens, J.A. (2004). A practical guide to dose-response analyses and risk assessment in occupational epidemiology. Epidemiology, 15(1), 63-70. PMID: 14712148.

88. Malloy EJ, Kapellusch JM, Garg A. (2017). Estimating and Interpreting Effects from Nonlinear Exposure-Response Curves in Occupational Cohorts Using Truncated Power Basis Expansions and Penalized Splines. Comput Math Methods Med. 2017:7518035. PMID: 29312462.

89. Cox, D. R. (1972). Regression models and life tables. Journal of the Royal Statistical Society: Series B, 34, 187-220.

90. Therneau, T. M., Grambsch, P. M., & Fleming, T. R. (1990). Martingale-based residuals for survival models. Biometrika, 77, 147–160. doi: 10.1093/biomet/77.1.147.

91. Lin DY, Wei LJ, Ying Z. Checking the Cox Model with Cumulative Sums of Mar- tingale-Based Residuals. Biometrika. 1993;80(3):557. doi:10.2307/2337177.

92. PASS; 2008, version 8.0.13, released 2010. NCCSS, LLC, Kaysville, Utah.

2.8 Project Publications

2.8.1 Publications in Calendar Year 2020

Thiese, M. S., Lu, M. L., Merryweather, A., Tang, R., Ferguson, S. A., Malloy, E. J., ... & Kapellusch, J. (2020). Psychosocial Factors and Low Back Pain Outcomes in a Pooled Analysis of Low Back Pain Studies. Journal of occupational and environmental medicine, 62(10), 810-815.

Tang et al. (2020). Evaluating different measures of low back pain among U.S. manual materials handing workers: comparisons of demographic, psychosocial, and job physical exposure. Human Factors (in Press).

Hegmann et al. (2020). Three Measures of Low Back Pain Incidence in a Large Consortium of Five Prospective Cohort Studies. Spine (Under Review).

2.8.2 Publications in Calendar Year 2019

Ferguson, S. A., Merryweather, A., Thiese, M. S., Hegmann, K. T., Lu, M. L., Kapellusch, J. M., & Marras, W. S. (2019). Prevalence of low back pain, seeking medical care, and lost time due to low back pain among manual material handling workers in the United States. BMC musculoskeletal disorders, 20(1), 1-8.

2.9 Inclusion Enrollment Table

***Study Title (must be unique):** Exposure-Response Relationships for Low Back Pain from Pooled Data

Comments: Data are for project #OH01916. Enrollments represent workers who were previously enrolled in three separate NIOSH funded projects and have now been combined into a single dataset. No workers are currently participating in this study or any of the three parent studies.

Racial Categories	Ethnic Categories									
	Not Hispanic or Latino			Hispanic or Latino			Unknown/Not Reported Ethnicity			Total
	Female	Male	Unknown/ Not Reported	Female	Male	Unknown/ Not Reported	Female	Male	Unknown/ Not Reported	
American Indian/ Alaska Native	4	4	0	0	0	0	0	0	0	8
Asian	25	21	0	0	0	0	0	0	0	46
Native Hawaiian or Other Pacific Islander	30	24	0	1	0	0	0	0	0	55
Black or African American	41	233	0	0	4	0	0	0	0	278
White	45	411	0	1	10	0	273	597	0	1,337
More than One Race	6	5	0	0	0	0	0	0	0	11
Unknown or Not Reported	0	7	0	61	173	0	0	0	0	241
Total	151	705	0	63	187	0	273	597	0	1,976

2.10 Inclusion of Children Document

Data were collected at places of employment. Children 18 years and older were not excluded from enrollment in the original studies. A total of 99 children had their data included in these pooled analyses (5.0% of participants). Because the children were legally adults, there were no differences in how they were treated by their employers. Similarly, the original investigators treated participants between 18-21 years identically to those 21 years of age or older.

2.11 Materials Available for Other Investigators

Data for this study are voluminous and intrinsically complex. Analyses are ongoing. Currently, data are not in formats suitable to share without restriction (dataset(s) for each analysis must be generated from raw information using scripts – assumptions that require detailed knowledge of the underlying data and methods are required to build these scripts). Investigators interested in using these data may contact the project PI (J. Kapellusch). The PI and co-Investigators are willing to partner with other investigators to further analyze and explore these data.

2.12 Appendix

Table 19: Descriptive Statistics for Individual and Biomechanical Variables

Variable	N	Mean ± SD	Min – Max	%
Age[A]	1976	36.3 ± 11.5	18 – 69	
Age[B]	1650	35.5 ± 11.3	18 – 69	
Gender[A]				
Female	487	---	---	24.6
Male	1489	---	---	75.4
Gender[B]				
Female	385	---	---	23.3
Male	1265	---	---	76.7
BMI[A]	1976	28.3 ± 6.1	15.8 – 85.7	---
BMI[B]	1650	28.0 ± 6.0	15.8 – 85.5	---
LBP Hx[A]				
No	1580	---	---	80.0
Yes	396	---	---	20.0
LBP Hx[B]				
No	1294	---	---	78.4
Yes	356	---	---	21.6
CULI[B]	1650	3.65 ± 2.30	0.20 – 36.54	---
pkCLI[B]	1650	3.30 ± 1.57	0.20 – 12.80	---
pkFILI[B]	1650	2.47 ± 1.07	0.10 – 7.55	---
Peak Weight (lbs)[B]	1650	45.8 ± 19.4	0.5 – 119.8	---
Peak Twisting (degrees)[B]	1650	57.5 ± 33.6	0 – 169.7	---
Peak Reaching (inches forward)[B,C]	1650	32.1 ± 6.6	10.9 – 43.3	---
Peak Bending (inches from floor)[B,D]	1650	12.9 ± 9.0	0 – 53	---
Total Frequency (Lifts per Minute)[B]	1650	2.4 ± 1.8	0.1 – 14.9	---

[A] Overall prevalence (i.e., maximum N)
[B] Prevalence Analyses Sample (i.e., complete baseline N)
[C] RNLE Horizontal Location of Hands, includes on-handed lifts
[D] RNLE Vertical Location of Hands