Cumulative Spine Loading and Clinically Meaningful Declines in Low-Back Function

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Objective: The objective was to assess the role of cumulative spine loading measures in the development of a clinically meaningful decline in low-back function.

Background: Cumulative spine loading has been a suspected risk factor for low-back pain for many years, yet the measures that characterize risk have not been well delineated.

Methods: A total of 56 cumulative exposure measures were collected in a prospective field study of distribution center workers. An individual's risk for a clinically meaningful decline in low-back function (true cases) was explored with daily, weekly, and job tenure cumulative exposure measures using univariate and multivariate statistical modeling techniques. True noncases were individuals with no decline in low-back function.

Results: An individual's risk for a clinically meaningful decline in low-back function (true cases) was predicted well versus true noncases (sensitivity/specificity = 72%/73%) using initial low-back function (p(n)), cumulative rest time, cumulative load exposure, job satisfaction, and worker age.

Conclusions: Cumulative rest time was identified as an important component for predicting an individual's risk for a clinically meaningful decline in low-back function.

Application: This information can be used to assess cumulative spine loading risk and may help establish guidelines to minimize the risk of a clinically meaningful decline in low-back function.

Keywords: low-back pain, biomechanics, epidemiology, occupational risk, surveillance

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HUMAN FACTORS
Vol. 56, No. 1, February 2014, pp. 29–43
DOI: 10.1177/0018720813496814

INTRODUCTION

Cumulative spine loading has been a suspected risk factor for low-back disorders over the past couple of decades. However, our understanding of cumulative spine loading and its association with risk is rather poor in that we do not know which cumulative loading measures represent the most predictive indicators of low-back disorder risk. Much of the interest in cumulative loading has been extrapolated from upper extremity field studies that have shown an increased risk of cumulative trauma disorders when exposed to repetitive work. In these studies the relationship between job-required hand force and repetition was associated with increased risk of upper extremity disorders such as carpal tunnel syndrome (Silverstein, Fine, & Armstrong, 1986, 1987).

The theory behind cumulative loading suggests that repetitive loading of tissues can weaken their tolerance and thereby reduce the ability of a worker to withstand force over time. In the spine, biomechanical studies have established that repetitive compressive loads could result in spine damage at submaximal levels of force application (Adams & Hutton, 1983; Liu, Njus, Buckwalter, & Wakano, 1983). Employing this logic, one needs to merely understand how much repetition under a variety of loading levels will weaken a structure to the point of failure. However, attempts to establish such limits for the low back have not been successful. In vitro studies of the spinal tissues have attempted to identify the amount of cumulative compressive load that would result in tissue disruption (Brinkmann, Biggermann, & Hilweg, 1988; Hansson, Keller, & Spengler, 1987), though attempts to characterize these relationships have not been able to account for much of the data variance (Callaghan, 2002). Further attempts to identify the level of repetitive loading that could cause damage have included shear force estimates (Yingling & McGill, 1999); however, few have been able to describe this trend using human samples of working age (Gallagher, Marras, Litsky, & Burr, 2005). Once compressive and shear loading combinations are considered along with various repetition rates, the response depiction rapidly becomes complex, and it becomes very difficult to determine thresholds of tolerance. In addition, in vitro studies are unable to account for adaptation that is expected to occur in vivo. Thus, it appears that a simple load-frequency threshold of tolerance for spine loading has been elusive for cumulative spine loading.

Given these challenges associated with laboratory-based biomechanical studies, several studies have attempted to better understand cumulative spine loading in vivo based on workplace (field) data collection studies. However, field studies do not permit the degree of control afforded by laboratory studies. Early field studies have used crude indicators of cumulative load exposure, such as hours worked in a particular posture, based on structured interviews and found relationships with radiographic diagnoses of spine problems (Seidler et al., 2001; Seidler et al., 2003). Others have found that crude measures of spine compression at work correlated with lost time (Village et al., 2005). Yet another study used technical experts to estimate cumulative spine load and found a dose–response relationship between the cumulative lumbar load and the acceleration of lumbar disc narrowing (Seidler et al., 2011). Kumar (1990), using a two dimensional load model, found that cumulative compression and shear was greater in those with low-back pain. Norman and colleagues (1998) employed two cumulative load measures (as assessed with a rudimentary biomechanical model) to estimate load over a shift. The final multivariate model reported by Norman et al. showed that workers in the top 25% of loading were 6 times more likely to report low-back pain than those in the lower 25% of exposure. Similarly, Kerr et al. (2001) found that cumulative disc compression as measured over a shift was associated with low-back pain reports. These field-based studies provide insight but few definitive thresholds to assess how much cumulative spine loading is too much cumulative spine loading.

The logic underlying cumulative spine loading and spine damage suggests that micro damage occurs at a rate that is faster than the tissue can repair or strengthen (Callaghan, 2006). Yet most studies that have attempted to study cumulative spine loading tolerance limits have largely ignored the tissue repair time associated with spinal loading. Tissue repair time appears to be an essential element of spine tissue health. Several efforts have described the nutrition pathway mechanisms by which spine loading relates to degeneration and tissue repair (Buckwalter, 1995; Lotz, 2004; Lotz & Chin, 2000; Urban & Roberts, 2003; Urban, Smith, & Fairbank, 2004); however, it has not been practical to examine these processes in laboratory in vivo studies involving humans. Several animal investigations have shown that inadequate rest time was associated with neuromuscular disorders (Courville et al., 2005; Hoops, Zhou, Lu, Solomonow, & Patel, 2007; Lu et al., 2008; Sbriccoli, Solomonow, Zhou, & Lu, 2007). In addition, inadequate rest time during the work cycle can be associated with proinflammatory cytokine reactions (Pinski et al., 2010). Thus, although many studies have examined the cumulative loading associated with spine disorders, there appear to be no studies that have explored the role of rest time in combination with cumulative spine loading.

Literature reviews have suggested that more quantitative measures of exposure can lead to a better understanding of musculoskeletal risk (National Research Council and Institute of Medicine, 2001). Although previous field studies have shown relationships between cumulative spine loading (measured in various ways) and low-back problems, these studies do not necessarily provide quantitative insight as to the characteristics of work exposure that are problematic. This lack of quantitative guidance may be due to several significant challenges associated with previous workplace-based studies. The first challenge in the workplace is to describe the work exposures (loading and timing characteristics) with enough fidelity to provide a meaningful quantitative understanding of the cumulative loading profile relative to the risk. Second, the temporal aspects of the work exposure are typically not defined in enough detail for useful analysis. Thus, issues such as rest time have not been adequately investigated. Third, it is extremely difficult to collect comprehensive loading information without interfering with the job, and it is also a challenge to describe the cumulative exposures over extended periods. Finally, low-back disorders have not been classified or described in a meaningful way to understand the nature of the low-back disorder and, thus, the risk. Thus, the aim of this study was to objectively quantify low-back disorders among distribution center workers and the associated cumulative spine loading exposures.

METHOD

Experimental Design

This study was a prospective field evaluation that quantitatively monitored low-back health effects (low-back kinematic function) of workers performing materials handling work in distribution centers as well as quantitatively documented the physical exposures in the workplace.

Initially, a baseline data collection effort was performed. All workers involved in manual materials handling tasks (i.e., order picking, truck loading/unloading, stock replenishment) in various distribution centers were invited to participate in the study. Workers who agreed to the study signed institutional review board consent forms and then were evaluated for health effects status.

Health effect evaluations consisted of a low-back functional assessment to measure low-back impairment status as well as a questionnaire. After the baseline health effects data were collected, but before the health effects follow-up physical exposure measures were collected from a subset of workers performing each job category within the distribution center. The number of workers recruited for work exposure measurements depended on the number of workers employed in the particular job. Between three and seven workers were randomly selected for monitoring on each job. Previous studies (Marras, Allread, Burr, & Fathallah, 2000) have determined that a minimum of three workers was necessary to adequately document the physical characteristics of a workplace.

At least 6 months after the baseline low-back health effects measures were collected; follow-up health effects measures were once again collected from all workers who were still assigned to the jobs of interest.

Data Collection Sites

Data collections occurred at distribution centers (DCs) where employees performed repetitive material handling tasks continuously throughout the day. Data were collected from grocery, automotive parts, clothing, and general merchandise DCs. Jobs within the DCs were identified relative to the department (or section) of work exposure. For example, within a grocery distribution operation there may be three to four jobs, depending on how orders are distributed. Usually employees lift or "select" in dry groceries, produce, frozen foods, or boxed meats. Therefore, a grocery facility with these four areas would potentially contribute four jobs to the database.

Overall, a total of 19 different DCs were included in the database. A total of 48 jobs were identified within these facilities. The types of DCs included grocery, auto parts, clothing, and general merchandise. The number of each type and number of jobs in each type have been reported previously (Marras, Lavender, Ferguson, Splittstoesser, & Yang, 2010).

Worker Database

DCs are notorious for high rates of dropout (Min, 2007). This was reflected in our sample. Originally, 888 workers were enrolled in this study. At follow-up 366 of the workers had left the job and were unavailable for follow-up. The job exposures for the dropout group were similar to those for individuals with a clinically meaningful decline in low-back function. A detailed description of the dropout group compared to those who remained on the job has been discussed elsewhere (Ferguson, Marras, Lavender, Splittstoesser, & Yang, 2014). Of the 522 remaining workers, 72 were eliminated from consideration because they no longer were assigned to the same job. Consequently, 450 workers were available for the health effects follow-up analysis, representing a follow-up rate of slightly more than 50%.

Health History, Work History, and Psychosocial Assessment

All workers were asked to fill out a survey that assessed their job tenure, hours worked per week and experiences as well as their psychosocial impressions of the work. These characteristics have been reported elsewhere (Marras, Lavender, Ferguson, Splittstoesser, & Yang, 2010). Employees were given a hat or T-shirt in exchange for participating in each health effect session of the data collections (baseline and follow-up).

Low-Back Functional Impairment Evaluation

To quantitatively document the functional status of the low back, workers were asked to participate in kinematic back functional assessments. This required workers to interact with a computer while wearing a clinical lumbar motion monitor (LMM) to document kinematic performance in three-dimensional space using the assessment protocol described previously in the literature (Ferguson & Marras, 2004). This low-back functional assessment required approximately 10 minutes. This procedure yields objective data (sagittal range of motion, velocity, and acceleration) describing the worker's back kinematic function and represents an independent, performance-based, low-back assessment. The model underlying this analysis has excellent sensitivity (90%) and specificity (92%) in its ability to correctly differentiate those with and without back pain (Marras et al., 1995; Marras et al., 1999). By comparing each employee's kinematic profile with that of a normative database, the model was able to quantify how that worker's kinematic function compares to that which would be expected of a person of that age and gender (expected normal kinematic function). The worker's kinematic back function is scaled relative to the expected normal kinematic function (for an individual) and is defined as the probability of normal or p(n). A probability of less than 0.5 indicates impaired function for an individual's age and gender, whereas a probability greater than 0.5 indicates healthy performance. This analysis is also able to identify whether a subject is magnifying their impairment (Marras, Lewis, Ferguson, & Parnianpour, 2000). A decrease in p(n) of at least 0.14 is considered clinically meaningful (Ferguson et al., 2009). This value was used as a minimum benchmark for defining low-back true cases; individual workers whose kinematic functional score decreased by 0.14 between the baseline measure of low-back function and the follow-up measurement were defined as low-back cases.

Figure 1. Moment monitor on subject.

Physical Exposure Sampling

Work exposure sampling was performed on 193 of the workers employed in the jobs of interest. This was a randomly selected subgroup of the 450 workers that participated in the health effects part of the study. Quantitative exposure data were obtained using custom instrumentation described previously (Marras, Lavender, Ferguson, Splittstoesser, & Yang, 2010). Figure 1 shows a worker wearing the exposure monitoring system while performing his job. The instrumentation system consists of an instrumented backpack that was worn by the worker. Instrumented handles were used to lift the load while they measured static and dynamic load characteristics and document the direction of effort. The handles emit ultrasound signals that are received by sensors

TABLE 1: Anthropometry for Health Effects and Physical Exposure Respondents

	Health Effects		Physical Exposure	
	Baseline (n = 888)	Follow-Up (n = 450)	Moment Monitor (n = 193)	p Value Follow-Up vs. Exposure
Age (years)	33.9 (10.7)	36.8 (10.9)	36.3 (10.9)	.594
Height (cm)	176.6 (9.3)	175.6 (9.9)	175.8 (8.9)	.091
Weight (kg)	85.1 (19.5)	85.6 (19.4)	82.8 (17.9)	.842
% male	85	82	83	.799

Note. Dropouts include job changes, no opportunity for follow-up. Health effects group is self-report; physical exposure was measured. Data presented as mean (standard deviation) unless otherwise indicated.

positioned around the backpack frame. The ultrasound receivers triangulate the handle location and thereby enable the backpack to document the travel path of the load relative to the spine. The backpack also contains accelerometers that document trunk motions. The system software translates the exposures relative to exposures about the L5/S1 disc. Detailed descriptions of the instrumentation and performance can be found elsewhere (Marras, Lavender, Ferguson, Splittstoesser, Yang, & Schabo, 2010). Force measurement accuracy was documented within 0.5 Kg (1.1 pounds), and position accuracy (average absolute error) is within 3.0 cm (1.2 inches). These calibrations represent accuracies that are 4 times more accurate than taking the measurement manually (Marras, Lavender, Ferguson, Splittstoesser, Yang, & Schabo, 2010). In addition, the system is unique in that it is capable of documenting dynamic load moment exposure at the worksite. This system enables the continuous monitoring and recording of three-dimensional hand locations relative to both the L5/S1 disc and the ground, the instantaneous load weight (static and dynamic), the orientation of the torso, and the timing of lifting events, and a variety of derived measures (e.g., moment arms, static and dynamic load moments, etc.). Data were continuously collected using the built-in microprocessor and stored on memory flash cards for later analysis. The data processing programs used the hand load exposure information to identify lift initiation and termination points and thereby identified the intervals of time during which lifting was occurring and the interlift (rest) periods. Overall, the system collected 390 variables for each lift performed by the worker.

Workers involved in physical exposure sampling were randomly chosen from the pool of workers performing the job. The workers were compensated for their participation with gift cards from area merchants. Each employee was monitored for up to 4 hours and was asked to perform his or her job and match his or her normal productivity rates.

Worker Anthropometry

Table 1 shows the basic anthropometric characteristics of the workers tested for health effects at baseline and follow-up as well as for the workers selected for exposure testing. As indicated in Table 1 the workers were relatively young and there were no statistically significant differences in anthropometric measures between the workers from which the physical exposures were collected compared to the health effects follow-up group.

Physical Exposure Database

The total physical exposure database in this analysis consisted of 59,796 lifting or lowering exertions. Custom software was developed to analyze each of the exertions. An exertion was defined as 3 pounds (1.5 pounds in each hand) experienced by the worker for more than 0.5 seconds. The 1.5 pounds in each hand was selected based on the accuracy of the force transducer (1.1 pounds). The rest time for each exertion was defined as the time since the last exertion. A total of 56 cumulative measures were calculated to represent exposures. These measures consisted of 28 cumulative load variables processed in two different ways: (a) integration of the signal over exertion time or (b) signal peak multiplied by the duration of exertion (Callaghan, Salewytsch, & Andrews, 2001). The integrated measures from each exertion were summed across the data collection time for that worker. The cumulative measures were multiplied by a scaling factor for that worker to derive an 8-hour day exposure. The data from the workers who wore the moment monitor were averaged together and assigned to each worker who worked that job for the daily exposure measure. The questionnaire data for the number of hours worked per week for each worker were multiplied by the daily exposure and used to define weekly exposure. The weekly exposure was multiplied by the questionnaire data regarding duration of employment on the job to define job tenure exposure. This analysis focuses on the association between cumulative (integrated) physical exposure characteristics and a clinically meaningful decrease in low-back kinematic function.

Data Analysis: Individual Low-Back Functional Decline Definitions

True individual cases were defined as those workers with a decrease in p(n) low-back function score of 0.14 or more (clinically meaningful decline or true case; Ferguson et al., 2009). Workers with a decline in p(n) from 0 to –0.14 (a nonmeaningful decline) were separated for analysis as neither cases nor noncases. Noncases were those with a p(n) change score of zero or more (true noncase).

Univariate Analyses

To test each of the integrated physical exposure measures between true noncases and true cases of a clinically meaningful change in low-back function, *t* tests were used. Classification and regression tree (CART; Breiman, Friedman, Olshen, & Stone, 1984; Steinberg & Colla, 1997) software was used to dichotomize the continuous dependent measures at one or more points for classification; however, in some cases the classification trend was inconsistent with cumulative loading expectations (trending in wrong direction; i.e., lower exposures resulted in true cases). Each dependent measure was assessed in CART to determine if the first cut point was in the expected direction. In addition, *t* tests were used to evaluate exposure differences between true noncases and the nonmeaningful decline in low-back function group as well as true cases versus the nonmeaningful decline in low-back function group.

Multivariate Analyses

The individual risk models indicated the risk of a clinically meaningful decline in low-back function. Three separate risk models were developed for individual risk based on the three definitions of cumulative measures: (a) daily risk model, (b) weekly risk model, and (c) job tenure risk model.

CART software was employed to select and assess the conditional relationship between the physical exposure variables. The CART analysis was offered physical exposure variables from each category of variables (i.e., load, timing, kinematics, psychosocial, etc.), and the analysis iteratively chose the variables and identified the value of the variable (cut point) that best distinguished between the true cases and true noncases. The first two or three variables from each category of variables selected by CART were used to build generalized linear models with SAS via “proc genmod.” The best multivariate models were selected based on three factors, consisting of (a) statistical significance of each variable entering the model, (b) the Akaike information criterion, and (c) model sensitivity and specificity. Sensitivity and specificity were calculated using the predicted values from the output of the generalized linear models with a cut point of 0.5. Relative risk values are reported for each model parameter. The models were developed and selected using the true noncases versus true cases (clinical meaningful decline in low-back function). The relative risk was also calculated for the true noncases versus nonmeaningful decline in low-back function as well as the relative risk between nonmeaningful declines versus true cases.

RESULTS

Based on our case definitions, the database yielded 126 workers with a clinical meaningful decline in low-back function (true cases), 115 workers with a nonmeaningful decline in low-back function, and 205 noncases with no decline in low-back function (true noncases).

Univariate Cumulative Individual Risk

Table 2 shows descriptive statistics (mean and standard deviation) for the 28 integrated variable true cases and true noncases as a function of daily, weekly, and job tenure cumulative exposure metrics examined in this study. The peak times duration measure results were similar to these integrated measures; therefore these measures are not presented here. This table also identifies statistically significant differences between the true cases and true noncases of a clinically meaningful decline in low-back function as well as identifies those variables that trend in the expected direction (true cases were associated with greater cumulative exposure) by the various exposure metrics. This table indicates that a large number of univariate cumulative measures of exposure are consistent with the expected trend when the exposure variables are considered as a function of daily exposure, yet progressively fewer cumulative exposure variables are associated with the expected trend as metrics are considered for weekly and job tenure exposures, respectively (Figure 2). Of the 56 cumulative measures examined, 49 (88%) of the daily measures trended in a direction consistent with cumulative loading expectations (Figure 2), but only 9 (16%) of the job tenure cumulative measures behaved in this manner. It is notable that the only univariate cumulative exposure variables that both were statistically different between true cases and true noncases as well as trended in the expected direction consisted of the duration of rest measure for both the weekly and job tenure definitions of cumulative exposure. As expected, univariate analyses of true noncases versus the nonmeaningful decline in low-back function group found no exposure measures with significant differences. Similarly, there were no univariate significant exposure measure differences between the true cases versus the nonmeaningful decline in low-back function group.

Multivariate Cumulative Models: Individual Risk Models

Three multivariate cumulative risk models were developed to describe how the combinations of exposure measures were associated with a meaningful decline in low-back function within an *individual worker* as a function of the various cumulative exposure definitions (daily, weekly, or job tenure). The best performing individual risk models for daily, weekly, and job tenure definitions of exposure time are shown in Tables 3, 4, and 5, respectively.

The daily model contained baseline low-back function (p(n)), integrated daily duration of rest, integrated forward static load moment, baseline job satisfaction, and baseline worker age. Table 3 illustrates that the relative risk measure for each of these factors was statistically significant when examining true noncases versus true cases. Furthermore, the model had a sensitivity and specificity of 72% and 73%, respectively. The cut points provide thresholds for how much or how little exposure created increased levels of risk. For example, a worker whose baseline functional performance is greater than 0.5 is 2.12 times more likely to have clinically meaningful decline in low-back function compared to a worker with a baseline score < 0.5. Table 3 also lists the relative risk for the model when considering the true noncases and the nonmeaningful declines in low-back function. As expected, the model performance was poorer in this case with most individuals being predicted as true noncases (i.e., specificity 91%). Finally, the daily model was also used on the nonmeaningful declines versus true cases. In this situation only the baseline functional performance relative risk was statistically significant. The model sensitivity was 78% and specificity was 50%.

Table 4 lists the weekly model relative risk values as well as sensitivity and specificity for the true noncases versus true cases, true noncases versus nonmeaningful declines in low-back function, and nonmeaningful declines versus true cases. As with the daily model, the weekly model contains baseline functional performance, job satisfaction, and baseline worker age. The weekly model also contains integrated weekly duration of rest as well as peak × duration weekly sagittal acceleration. The relative risk values for true noncases versus true cases indicate that all the factors in the model were statistically significant. The sensitivity was 62% and specificity was 81%. The baseline functional performance

TABLE 2: Trunk Loading, Position, and Timing Variables Means (standard deviations) and *p* Values Integrated Daily, Weekly, and Job Tenure

	Daily Integrated			Weekly Integrated			Job Tenure Integrated		
Variable	True Noncases	True Cases	*p* Value	True Noncases	True Cases	*p* Value	True Noncases	True Cases	*p* Value
Load variables									
Load (N)	110956.8 (64441)	113968.5 (67765.7)	.686†	4544213.8 (304965)	4477673.2 (3104819)	.848	20562843.7 (25406315.0)	18458824.5 (22929443.0)	.449
Dynamic lift force (N)	102161.8 (64463.9)	104859.4 (68201)	.718†	4173902.8 (3032890)	4100424.6 (3080287)	.832	18821016.1 (24601329.0)	16716517.4 (22157354.0)	.434
Dynamic slide force (N)	39595.2 (22304)	41483.9 (24264)	.470†	1613173.8 (1027088)	1635568.1 (1103654)	.852	7335105.3 (8758966.0)	6930808.9 (8179874.1)	.676
Dynamic lift/slide force (N)	116396.2 (69580)	120066.8 (74055)	.650†	4753839.3 (3271170)	4708006.8 (3365786)	.903	21473041.4 (27050745.0)	19427949.7 (24571752)	.490
Static forward-bending load moment (Nm)	36163.5 (19659)	36733.1 (19435.7)	.797†	1478840.3 (931081.4)	1437254.3 (892515.7)	.689†	6708994.5 (7870379.0)	5857516.7 (6663195.9)	.209†
Static side-bend load moment (Nm)	8026.1 (4601)	8239.2 (4819)	.688†	327914.4 (212793)	323154.2 (218041)	.845	1483307.9 (1766637.0)	1322836.9 (1579836.0)	.405
Static transverse plane load moment (Nm)	37704.0 (20517)	38325.6 (20386.6)	.789†	1541573.7 (970065)	1499741.4 (935252)	.700†	6989659.9 (8195694.0)	6111998.7 (6968567.0)	.300†
Dynamic forward-bending load moment (Nm)	33536.6 (19731)	34055.3 (19786)	.817†	1368006.7 (927350)	1326257.7 (892281)	.687	6186309.9 (7623083.0)	5347743.9 (6443130.2)	.286
Dynamic side-bending load moment (Nm)	7508.0 (4636.6)	7705.2 (4882)	.713†	306090.6 (213525)	301086.0 (218275)	.838	1377901.8 (1721534.0)	1216639.3 (1532313.8)	.390
Dynamic transverse plane load moment (Nm)	34990.5 (20599)	35557.6 (20747)	.808†	1427099.8 (966690)	1385030.5 (935168)	.698	6448997.1 (7941100)	5583607.4 (6739827.7)	.291
Dynamic forward-bending resultant (sagittal) moment (Nm)	36393.1 (20358)	37415.8 (21168)	.662†	1482133.0 (955682)	1453491.5 (948067)	.791	6686297.3 (8052906)	5903691.2 (6973054.7)	.368†
Dynamic resultant moment (Nm)	38093.7 (21336.5)	39183.7 (22228)	.657†	1551451.4 (1000289)	1523416.6 (996788)	.804	6997575.9 (841965)	61900926.1 (7317246.9)	.375
Position variables									
Sagittal position (degrees)	40115.9 (22821)	39588.7 (21051)	.834	1645513.8 (1076390)	1559742.8 (983046)	.468	7365113.8 (8610951)	5986059.8 (6435721)	.098
Sagittal flexion velocity (deg./sec.)	25074.9 (13346)	27152.8 (15081)	.192†	1023820.6 (608404)	1059728 (673638)	.617†	4461677.4 (5188137)	4269910.1 (5085815)	.743
Sagittal extension velocity (deg./sec.)	–36240.8 (21728)	–36127.4 (22673.4)	.964†	–1478912.6 (1001853)	–1423955.4 (1002891)	.629	–6750997.2 (8273337)	–5984103.1 (7458416)	.396
Sagittal acceleration (deg/sec.^{2})	243550.5 (138070)	257455.2 (15565)	.397†	9926315.9 (6297083)	10111551 (6923610)	.803†	44211616.4 (53705807)	42441752.7 (54051754)	.772
Sagittal deceleration (deg/sec.^{2})	–236922.9 (136333)	–250473 (153887)	.404†	–9666468.3 (6237801)	–9850806.1 (6854640)	.802†	–43241334.6 (53157280)	–41607055.5 (53449358)	.787

(continued)

TABLE 2: (continued)

	Daily Integrated			Weekly Integrated			Job Tenure Integrated		
Variable	True Noncases	True Cases	*p* Value	True Noncases	True Cases	*p* Value	True Noncases	True Cases	*p* Value
Lateral right position (degrees)	6492.7 (4264)	6411.4 (4299)	.867†	268908.4 (203074)	252957.3 (187736)	.476	1247753.1 (1623286)	1026720.3 (1257766)	.167
Lateral left position (degrees)	–5415.4 (2605)	–5577.1 (2778)	.593†	–220332.9 (117285)	–218734.2 (125024)	.907†	–967564.9 (1013023)	–881111.8 (934618)	.439
Lateral right velocity (deg/sec.)	30047.4 (15844)	30966.3 (17448)	.622†	1232799.8 (746617)	1218440.6 (771726)	.867†	5555230.1 (6443190)	4994310.4 (5841368)	.427
Lateral left velocity (deg./sec.)	–30531.6 (16164)	–30989 (17506)	.809†	–1251894.3 (760335)	–1220693.6 (777696)	.720	–5657241.6 (6549109)	–5022245.5 (5888074)	.375
Lateral acceleration (deg/sec.^{2})	270067.3 (144804)	278194.6 (15383)	.634†	11086387.7 (6846113)	10957192.9 (7077530)	.870†	49956361.5 (58622958)	45038446.7 (53274993)	.444
Lateral deceleration (deg/sec.^{2})	–271795.9 (145514)	–278521 (159772)	.694†	–11149028.0 (6859277)	–10968443.0 (7083316)	.819†	–50294701.5 (58857841)	–4514064.0 (53552693)	.425
Timing variables									
Duration (seconds)	1916.24 (926.1)	1902.8 (973.4)	.900	78621.72 (44368.46)	74620.88 (43610.92)	.424	354452.71 (392348)	306690.35 (335855)	.258
Duration of rest (seconds)	11345.5 (3473.4)	10701.1 (3391.2)	.099†	462939.3 (174793.6)	410958.5 (156558.5)	.007*†	2047085.02 (1826062)	1687709.38 (1453216)	.049*†
Duration of get (seconds)	469.6 (236.5)	439.4 (232.5)	.258	19258.4 (11201.2)	17303.3 (10400.7)	.114	88182.92 (97405)	72079.89 (77083)	.064
Duration of carry (seconds)	1093.5 (560.2)	1133.2 (613.8)	.547†	44810.3 (26286.8)	44249.41 (27185.7)	.853	199329.17 (228473)	179729.77 (209242)	.097
Duration of place (seconds)	353.1 (193.9)	330.1 (178.4)	.281	14553.1 (9303.9)	13068.2 (8121.5)	.141	66940.74 (77747)	54880.85 (56235)	.435

Note. Units for daily integrated are per day, units for weekly integrated are per week, and units for job tenure are over the individual's time on the job.
†Cut point went in the correct direction.
*Statistical differences between low and high risk.

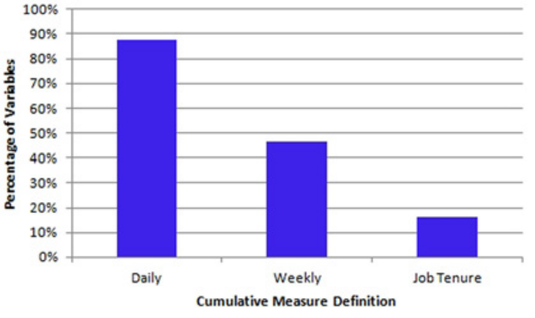

Figure 2. Percentage of measures cutting in the correct direction as a function of the cumulative measure definition.

measure indicated the highest relative risk followed by the weekly sagittal acceleration exposure measure and weekly duration of rest are nearly identical at 1.69 and 1.64, respectively. The job satisfaction and the age measure had lower relative risk values than the cumulative exposure measures. The true noncases versus nonmeaningful decline group as well as the nonmeaningful declines versus true cases results for the weekly model were similar to those of the daily model.

The job tenure multivariate model is shown in Table 5. The model contains the baseline functional performance, integrated job tenure duration of rest, job tenure peak × duration of forward static load moment, baseline supervisor support, and baseline worker age. It should be pointed out that the forward static load moment had a confidence interval of 0.99 to 12.88, so it was not statistically significant. Table 2 indicates that only 9 of the job tenure variables cut in the correct direction. One of these measures was duration of rest, and all the other measures were used in models with the combination of baseline functional performance, baseline supervisor support, and worker age at baseline. However, none of the job tenure exposure measures that cut in the correct direction were statistically significant. To be consistent with the weekly and daily models that employed personal, psychosocial, and physical exposure measures, this model also employed these categories of variables. It is interesting to note that the relative risk values for baseline functional performance and duration of rest were greater than those for the daily and weekly exposure models (Table 5).

Among the daily, weekly, and job tenure models there are some commonalities. First, all contain the baseline functional performance measure. Second, all three models contain the exposure measure duration of rest and the

TABLE 3: Multivariate Relative Risk Model for *Daily* Exposure as a Function of Injury Group

Variable Name	Cut Point	True Noncases vs. True Cases (reference group true noncases)	True Noncases vs. Nonmeaningful Decline in Low-Back Function (reference group true noncases)	Nonmeaningful Decline vs. True Cases (reference group nonmeaningful loss)
Baseline functional performance	>0.5	2.12 (1.58–2.83)	1.52 (1.12–2.05)	1.80 (1.27–2.56)
Integrated daily duration of rest (seconds)	< 9886	1.41 (1.11–1.80)	1.43 (1.05–1.94)	1.17 (0.93–1.48)
Integrated forward static load moment (Nm)	>32217	1.28 (1.01–1.63)	1.45 (1.06–1.98)	0.99 (0.78–1.25)
Baseline job satisfaction	<2.5	1.34 (1.05–3.70)	1.18 (0.87–1.60)	1.15 (0.87–1.51)
Baseline age (years)	32 < age < 44	1.39 (1.13–1.72)	1.22 (0.90–1.64)	1.18 (0.93–1.49)
Model sensitivity (%)		72	25	78
Model specificity (%)		73	91	50

TABLE 4: Multivariate Relative Risk Model for *Weekly* as Function of the Injury Group

Variable Name	Cut Point	True Noncases vs. True Cases (reference group true noncases)	True Noncases vs. Nonmeaningful Decline in Low-Back Function (reference group true noncases)	Nonmeaningful Decline vs. True Cases (reference group nonmeaningful loss)
Baseline functional performance	>0.5	2.95 (1.99–4.37)	1.55 (1.14–2.10)	1.68 (1.99–2.36)
Integrated weekly duration of rest (seconds)	<390718	1.64 (1.21–2.24)	1.22 (0.91–1.64)	1.35 (1.02–1.78)
Peak*duration weekly sagittal acceleration (deg/sec^2)	>101349760	1.69 (1.16–2.46)	1.02 (0.49–2.13)	1.81 (1.17–2.82)
Baseline job satisfaction	<2.5	1.43 (1.08–1.89)	1.21(0.89–1.63)	1.22 (0.90–1.64)
Baseline age (years)	32 < age < 44	1.45 (1.17–1.81)	1.24 (0.92–1.66)	1.18 (0.95–1.47)
Model sensitivity (%)		62	9	70
Model specificity (%)		81	98	54

TABLE 5: Multivariate Relative Risk Model for *Job Tenure* as Function of the Injury Group

Variable Name	Cut Point	True Noncases vs. True Cases (reference group true noncases)	True Noncases vs. Nonmeaningful Decline in Low-Back Function (reference group true noncases)	Nonmeaningful Decline vs. True Cases (reference group nonmeaningful loss)
Baseline functional performance	>0.5	3.20 (2.17–4.71)	1.55 (1.14–2.09)	1.77 (1.24–2.52)
Integrated job tenure duration of rest (seconds)	<4186846	2.17 (1.14–4.12)	1.21 (0.78–1.87)	1.59 (0.86–2.94)
Peak*duration forward static load moment (Nm)	>1070282	3.56 (0.99–12.88)	1.07 (0.61–1.87)	2.75 (0.80–9.48)
Baseline supervisor support	<2.5	1.64 (1.04–2.60)	2.14 (1.20–3.81)	0.90 (0.62–1.32)
Baseline age (years)	32 < age < 44	1.47 (1.18–1.83)	1.20 (0.89–1.61)	1.17 (0.93–1.48)
Model sensitivity (%)		66	18	75
Model specificity (%)		76	95	52

personal factor of age. The models differ on the specific psychosocial measure with the daily and weekly models containing job satisfaction variables, whereas the job tenure model contained supervisor support. Finally the second job exposure measure was different for each model. The daily model contained forward static bending moment calculated via the integrated signal, whereas the job tenure model included the forward static bending moment (calculated via

TABLE 6: Univariate Relative Risk and (95% confidence interval) for Cumulative Duration of Rest by Definition and Individual Functional Change Groups

Variable Name	Cut Point	True Noncases vs. True Cases (reference group true noncases)	True Noncases vs. Nonmeaningful Decline in Low-Back Function (reference group true noncases)	Nonmeaningful Decline vs. True Cases (reference group nonmeaningful loss)
Integrated daily duration of rest	<9886	1.47 (1.12–1.94)	1.22 (0.92–1.64)	1.16 (0.91–1.48)
Integrated weekly duration of rest	<395449	1.67 (1.25–2.32)	1.25 (0.94–1.68)	1.25 (0.97–1.62)
Integrated job tenure duration of rest	<4186849	2.20 (1.11–4.37)	1.11 (0.72–1.74)	1.70 (0.92–3.19)

peak × duration) and the weekly model included the sagittal acceleration (calculated via peak × duration). In comparing sensitivity and specificity of the daily, weekly, and job tenure model, the daily model has the best balance between sensitivity and specificity. In addition, all the relative risk measures were statistically significant for the true noncases versus true cases. Thus, overall the daily model was selected as the best predictor of individual risk.

As shown in Tables 3 to 5, the most powerful component in these multivariate models of an individual low-back risk was the baseline functional performance, with a relative risk of 2.12 (CI = 1.58–2.83) for the daily exposure model, 2.95 (CI = 1.99–4.37) for the weekly model, and 3.20 (CI = 2.17–4.71) for the job tenure model. Most interesting, baseline functional performance was the only measure that was statistically significant in the true noncases versus nonmeaningful decline as well as the nonmeaningful decline versus true cases for daily, weekly, and the job tenure models. This further illustrates the importance of baseline functional performance for predicting low-back health in the future.

DISCUSSION

This effort has shed light on several important aspects of low-back disorder risk interpretation as related to work. First, initial low-back status, as measured by a quantitative low-back function measure (p(n)), is an important component of future low-back functional status. This is a measure of the initial condition of the worker's back and represents a logical start point for risk interpretation. Although many ergonomics studies declare that work risk can be minimized for all, this finding suggests that initial low-back functional status might be an often overlooked component of risk interpretation.

Second, several of the analyses associated with this assessment have indicated that cumulative rest duration is an important yet often overlooked metric for the assessment of low-back disorder risk. This measure was the only statistically significant univariate exposure metric capable of distinguishing true cases and true noncases. In addition, it was a significant factor in the multivariate models predicting daily, weekly, and job tenure individual risk. The notion that adequate rest time is an important component of risk fits well with our knowledge of tissue repair and adaptation of spine tissue. Although it is well known that human tissues become stronger and adapt to increased load demands (Wolff's law), this adaptation process depends heavily on adequate recovery (rest) time as well as delivery of nutrients for repair that occurs during rest time. Although task force and frequency are known to be important factors for musculoskeletal risk, few ergonomic risk assessment models consider the cumulative duration of rest in the assessment of low-back disorder risk. However, the duration of rest makes a great deal of sense from a physiologic standpoint. It may be that task frequency is simply a surrogate for cumulative rest time. Rest time may have more meaning from a duty cycle standpoint than does task frequency. Certainly, this concept provides the underpinning for future investigations.

Third, although some daily, weekly, and job tenure cumulative measures all trended in the expected direction, many more daily exposures were trended in the expected direction than weekly or job tenure exposures. However, only cumulative job tenure and cumulative weekly rest time exposures were statistically different between the true cases and true noncases of a clinically meaningful decline in low-back function in the univariate analyses. Table 6 shows the univariate relative risks associated with these rest duration exposure variables. This table indicates that the job tenure rest time had the highest relative risk with workers who are allowed less than 4,186,849 seconds (over their job tenure) being 2.2 times more likely to have a clinically meaningful decline in low-back function. The daily duration of rest had a relative risk of 1.47 for those with less than 9,886 seconds of rest per day. As expected the univariate rest measures were not significant for true noncases versus nonmeaningful declines or nonmeaningful declines versus clinically meaningful declines.

It is not surprising that the nonmeaningful decline in low-back function group did not separate well from the true noncases or the true cases. This group has shown a functional decline in low-back performance; however the decline has not reached the point of being a clinically meaningful decline. As such these individual workers should not be considered cases for this study. These individual workers may be at increased risk for further decline and should be monitored closely for further decline. In an ideal world the research would have captured another follow-up at 1 year to determine if these workers went on to become cases. However, given the high turnover rates among DC workers it would be highly unlikely that workers would be available for further evaluation.

Collectively, these results indicate that we need to reconsider the meaning and role that cumulative loading plays in low-back disorder risk. It appears that cumulative recovery time is equally as important, if not more important, to consider as cumulative loading of the tissue. Ergonomists need to consider the cumulative rest time available to the worker in a given work week.

ACKNOWLEDGMENTS

This project was funded by the National Institute for Occupational Safety and Health (NIOSH) via Grant No. 1UO1 OHO7313-01.

KEY POINTS

- A multivariate individual risk model containing initial low-back impairment (p(n)), cumulative rest time, cumulative loads, job satisfaction, and worker age predicted a clinically meaningful decline in low-back function well.
- Cumulative rest time during work was a key univariate indicator of a decline in low-back function.
- Daily definition of cumulative exposure typically produced the best risk models.

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Date received: January 5, 2013
Date accepted: June 17, 2013