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Development and validation of an easy-to-use risk assessment tool for cumulative low back loading: The Lifting Fatigue Failure Tool (LiFFT)

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ABSTRACT

Recent evidence suggests that musculoskeletal disorders (MSDs) may be the result of a fatigue failure process in affected tissues. This paper describes a new low back exposure assessment tool (the Lifting Fatigue Failure Tool [LiFFT]), which estimates a "daily dose" of cumulative loading on the low back using fatigue failure principles. Only three variables are necessary to derive the cumulative load associated with a lifting task: the weight of the load, the maximum horizontal distance from the spine to the load, and the number of repetitions for tasks performed during the workday. The new tool was validated using two existing epidemiological databases: the Lumbar Motion Monitor (LMM) database, and a database from a U.S. automotive manufacturer. The LiFFT cumulative damage metric explained 92% of the deviance in low back disorders (LBDs) in the LMM database and 72–95% of the deviance in low back outcomes in the automotive database (depending on the outcome measure). Thus, LiFFT is practitioner friendly and its cumulative damage metric highly related to low back outcomes.

1. Introduction

Low back pain (LBP) is a common and burdensome musculoskeletal disorder (MSD) with lifetime prevalence estimates ranging from approximately 40–80% (Balagué et al., 2012; Calvo-Muñoz et al., 2013; Hoy et al., 2012; Woolf and Pfleger, 2003). According to findings from the 2010 Global Burden of Disease study, LBP was observed to be the greatest contributor to global disability in terms of years lived with disability, and the sixth highest contributor to "overall burden" when measured in disability-adjusted life years of all 291 conditions studied (Hoy et al., 2014). The condition is also very costly. A recent systematic review of the literature estimated that LBP in the United States has a combined (direct and indirect) cost that ranges from $19.6 to $118.8 billion (Dagenais et al., 2008). However, an alternative estimate of $84.1 to $624.8 billion based upon the median proportion of direct (14.5%) versus indirect (85.5%) costs obtained from eight international studies was also suggested by the authors since the initial estimate was considered potentially inaccurate with respect to indirect costs.

Occupational exposure to manual lifting and other ergonomic stressors has been associated with LBP (Coenen et al., 2013; da Costa and Vieira, 2010; Manchikanti et al., 2014; Punnett et al., 2005). Specifically, it has been estimated that 37% of LBP may be attributed to work-related "ergonomic stressors" (Punnett et al., 2005) and that those stressors were responsible for 21.7 million disability-adjusted life years in 2010 alone (Driscoll et al., 2014). Several risk assessment tools have been developed over the past several decades to evaluate LBP risk resulting from manual lifting tasks. Among the most notable are the NIOSH Work Practices Guide for Manual Lifting (1981), the revised NIOSH lifting equation (RNLE; Waters et al., 1993), the Liberty Mutual Manual Materials Handling Tables (Liberty Mutual, 2004), and the Lumbar Motion Monitor (LMM) model (Marras et al., 1993).

The most well-known and widely-used tool among the ergonomics community is the RNLE (Dempsey et al., 2005; Waters et al., 1993, 1994). Despite its notoriety (Lu et al., 2016), the RNLE has been observed to "not (be) as robust as the widespread adoption implies, particularly with respect to comprehensive exposure assessments of jobs" (Dempsey, 2002; p. 287). Several additional procedures have been developed to expand upon the methods originally provided by NIOSH to estimate the relative magnitude of physical stress across an entire work shift (Garg and Kapellusch, 2016; Waters et al., 2007). While strong contributions to the scientific literature, these extensions to the RNLE are more complicated than the original RNLE and may not be practical for

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application by many occupational health and safety practitioners in the field. In addition, the rationale provided for both the assessment of multiple tasks and the magnitude of the reduction of the recommended weight limit (RWL) or increases in the lifting index (LI) are somewhat vague.

A growing body of evidence suggests that MSDs such as LBP and other low back disorders (LBDs) may be the result of a fatigue failure process (Gallagher and Schall, 2016). A major benefit of fatigue failure theory is that validated methods of predicting cumulative damage (CD[1]) for both mono-task jobs and jobs containing highly variable loading circumstances are available. The purpose of this paper is to introduce a new low back risk assessment tool based on fatigue failure principles, the Lifting Fatigue Failure Tool ("LiFFT"), that can be used to estimate cumulative spinal loading associated with lifting tasks with three simple inputs (load weight, peak horizontal distance from spine to load, and repetition). We describe the model logic and development of the tool, and provide validation against two existing epidemiological databases. One database is comprised of mono-task jobs (Marras et al., 1993; Zurada et al., 1997), the other is comprised of jobs involving as many as six different tasks, for which CD was summed across tasks (Sesek, 1999).

2. Methods

2.1. Model logic

Our goal in developing this tool was to develop a user-friendly method to estimate the risk of LBP/LBDs resulting from CD associated with variable magnitude loads and lifting repetitions. The LiFFT model uses the Peak Load Moment (PLM), or the weight of the lifted object multiplied by the horizontal distance of the load to the spine, and the number of lifting repetitions for each individual task as input variables. Estimates of CD were developed by estimating the spinal compression associated with each LM, comparing these compression estimates to the compressive strength of an "average" spine (approximately 6 kN; Jager and Luttmann, 1991), and multiplying the calculated damage per cycle (DPC; derived from studies of fatigue failure of spinal motion segments) by the number of repetitions experienced during the task at hand.

Cadaveric lumbar motion segments exposed to repetitive loading at different levels of compression exhibit a typical fatigue failure response, with fewer cycles to failure at high levels of loading and *vice versa* (Brinckmann et al., 1988; Gallagher et al., 2007). It was assumed that the same relationship holds *in vivo* (Andarawis-Puri and Flatow, 2011). Experimental data on cadaveric lumbar spines was examined to develop a relationship between cycles to failure and the ultimate strength of previously studied lumbar spine specimens. Specifically, data from two studies (Brinckmann et al., 1988; Gallagher et al., 2005, 2007) were analyzed using a Weibull approach to estimate the probability of spine failure at varying levels of estimated ultimate strength of motion segments, where predicted ultimate strength was calculated using the procedure outlined by Brinckmann et al. (1988) (Fig. 1).

In the case of censored observations (i.e., spines that did not meet the failure criterion upon reaching the maximum number of loading cycles), estimates were made regarding the number of cycles to reach a given criterion level of damage (10 mm displacement). Specifically, this was accomplished by determining the amount of displacement experienced in the number of maximum cycles for the study and extrapolating the number of cycles anticipated to reach the criterion displacement using linear estimation. An exponential relationship was developed to describe cycles to failure at different percentages of Ultimate Strength using the values for characteristic failure life of spines at various percentages of US (20–30%, 30–40%, 40–50%, 50–60%, and 60–70%). The relationship was characterized by the following equation:

$$\text{Cycles to Failure} = 902{,}416 * e^{-0.162 * \%US} \quad (1)$$

where *%US* is the percentage of the ultimate strength for a motion segment. From this relationship, it was possible to estimate the expected number of cycles to failure at different percentages of ultimate strength, and the inverse – the expected DPC at each %US.

We then estimated the compressive load associated with specific PLMs using a static biomechanical model (Bloswick and Villnave, 2000). Analyses were performed in an upright posture using an individual of average anthropometry (blended male and female), and varying PLMs were analyzed to develop an estimate of the compressive loads associated with various PLMs. Regression techniques were used to develop an equation defining the relationship. Using data from Jager and Luttmann (1991), we calculated the US of an "average" spine for the working age population (approximately 6 kN), again using blended males and female data for specimens aged 20–60. This allowed us to relate the "average" compressive load for a specified PLM with respect to an "average" spine, which could then be related to the percentage of US to allow estimation of the DPC at a specified level of LM. [We use the PLM, following (Marras et al., 1993).] The DPC is then multiplied by the number of repetitions performed to estimate the total CD associated with that task.

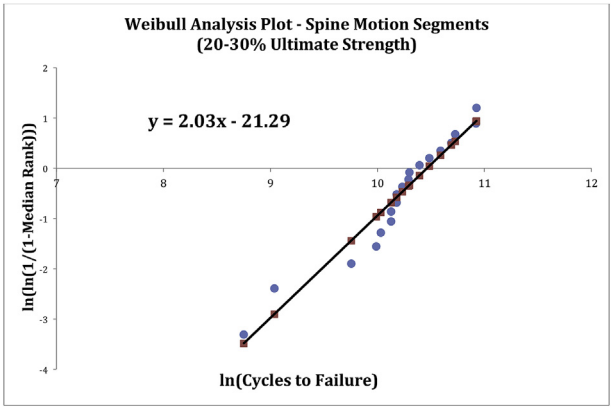

Fig. 1. A typical Weibull analysis for motion segments tested at 20–30% of the spine's Ultimate Stress (US). The horizontal scale of the Weibull data plot displays the log fatigue life, while the vertical scale represents the cumulative percentage of failures. Blue circles represent the combined data from Brinckmann et al. (1988) and Gallagher et al. (2007), and the red squares represent the Weibull distribution based on these data points. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Estimating risk for a low back outcome with LiFFT

Three measurements are required by a user of LiFFT to estimate the CD associated with a lifting task. These include: (1) the total number of repetitions (i.e., lifts) performed by a worker for a particular work task, (2) the weight of the object being manually handled, and (3) the maximum horizontal distance from the L5-S1 vertebral segment of the worker performing the lift to the center of the load being handled by the worker (Fig. 2). The greater trochanter (hip joint) can be used as an estimate of the position of L5-S1. If several objects with different weights are handled, each

[1] CD: Cumulative Damage; DPC: Damage Per Cycle; PLM: Peak Load Moment.

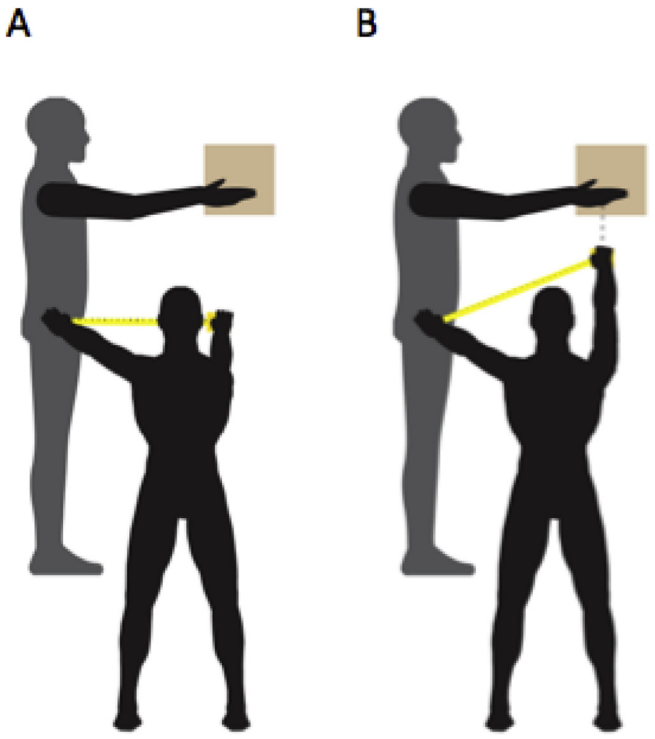

Fig. 2. A. Illustration of correct measurement of the maximum horizontal distance from the L5-S1 to the center of the load being handled. B. Incorrect method of measuring distance from L5-S1 to the center of the load (after Marras et al., 1999).

object should be individually measured and treated as a separate work task. The horizontal distance may be measured by the task analyst with a tape measure.

Prior to using LiFFT, a task analysis is recommended to properly define all relevant work tasks that comprise a job. While it would be ideal to measure the horizontal distance from the L5-S1 vertebral segment to the center of the weight being handled as well as the weight of each box for every single lift, this is not practical in the vast majority of situations. In general, we recommend following a "sampling approach" that requires that task data be obtained from a subset of the lifts to determine a representative lift that occurs during a work shift. Similar to other recently proposed lifting tools, the number of samples observed will depend upon the range of variability of the lifting tasks performed during the day (Waters and Dick, 2015). Marras et al. (1999) have suggested observing 7–10 repetitions as a general rule of thumb. However, it is important to note that this may not be possible for infrequent lifts (that also may happen to be the heaviest or most awkward, and have the largest peak moment). Therefore, the more frequent a job task, the more task cycles we recommend be observed to ensure that a representative lift be captured.

The simplest case where LiFFT can be applied is a mono-task scenario involving a worker who performs one consistent type of lift per day. For example, assume a worker lifts a 13 kg load from the ground and places the center of mass of that load 40 cm. (along the horizontal axis) from the center of the L5-S1 vertebral segment of the worker on a waist-high table 400 times in one day (Fig. 3). The estimated CD accrued during this task can be calculated by first multiplying the peak horizontal lever arm (40 cm) by the load (13 kg) to determine the PLM (40 cm × 13 kg = 51 Nm). That value is then converted to an estimate of task CD by multiplying this result by the number of repetitions performed in the day (400) and the DPC estimate of 0.000011, as derived in Section 2.1. In this scenario, it is estimated that an average male worker will accrue a CD daily dose of 0.0043, a figure associated with an estimated risk of 25.39% of experiencing a LBD (i.e., moderate risk [yellow]).

A strength of LiFFT is the simple extension of the tool to examine jobs involving multiple tasks and the calculation of an overall estimate of cumulative risk associated with a multi-task job. An example of a multiple task analysis is illustrated in Fig. 4. The job being analyzed is comprised of five separate lifting subtasks, and the CD for each is analyzed separately. Each individual subtask is categorized as low risk (green, < 25% risk of LBP), moderate risk (yellow, between 25 and 50% risk of LBP), or high risk (red, > 50% risk of LBP) using a "heat map". The estimated CD accrued during the entire work day may be calculated by summing the CD estimates for each subtask. In this case, while individual tasks are categorized as low or moderate risk, when the CD estimates for each task are summed, this combination of lifting tasks results in an estimated 35% risk of LBD (moderate risk range). It should be noted that the LiFFT tool provides the percentage of the cumulative load associated with each individual task, which can be used to prioritize tasks for risk reduction. In this example, subtask 4 accounts for 56% of the total cumulative load and would merit priority attention for job redesign. For example, simply reducing the horizontal distance to 24 cm for this task would reduce the overall LBP risk by approximately 10%.

One other aspect of the LiFFT tool can be noted from this example. It can be seen that task five involves a relatively high moment, but only 35 lifts of this sort are performed per day. The model suggests that such a task (by itself) remains acceptable. However, it should be realized that with such a task, every additional lift would lead to rapidly escalating CD.

2.3. Validation of LiFFT

We used two databases that contained the requisite information regarding PLM and the number of lifts performed for each task by individuals as well as their associated LBD or LBP health outcomes to validate LiFFT. The first was the LMM database described by Marras et al. (1993) and presented in Zurada et al. (1997). This database consists of two levels for LBD outcome. Low-risk jobs were categorized as those having no injuries and no turnover for the preceding three-year period. High-risk jobs were those having at least 12 injuries per 200,000 h of exposure. The former category had a total of 124 jobs and the latter consisted of 111 jobs. A wide range of manufacturing jobs was represented in this database.

The second database was from an epidemiological study examining MSD outcomes from a large automotive manufacturer. Data were analyzed from a database consisting of 667 manufacturing jobs. The database included historical injury data for the analyzed jobs as well as symptom interviews for 1022 participants (Sesek, 1999). A total of 304 workers who performed manual material handling tasks were analyzed in the LiFFT tool validation. Of these, six subsets (each having different LBP case/control definitions), were analyzed, as discussed in further detail below. These subsets ranged from 179 to 304 subjects. The subjects ranged in height from 147 to 203 cm (mean = 174.8 cm ± 9.4), weighed between 45 and 159 kg (mean = 84.8 kg ± 17.7), and were 20–70 years of age (mean = 41.6 years ± 10.9). The subjects were 72.7% male and 27.3% female. Researchers had no personal information regarding participants beyond height, weight, age, gender, and self-reported level of discomfort. All data were analyzed in aggregate.

2.4. Validation using LMM database (Marras et al., 1993; Zurada et al., 1997)

PLM and lifting frequency (lifts/hour) were variables employed

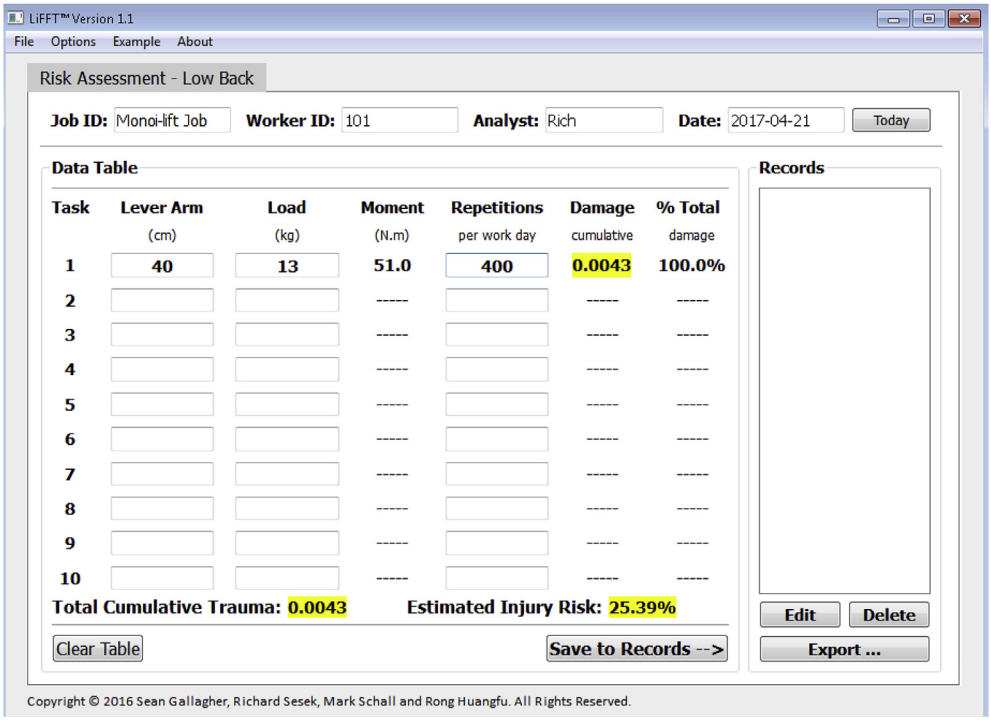

Fig. 3. Example of a mono-task lifting analysis using LiFFT.

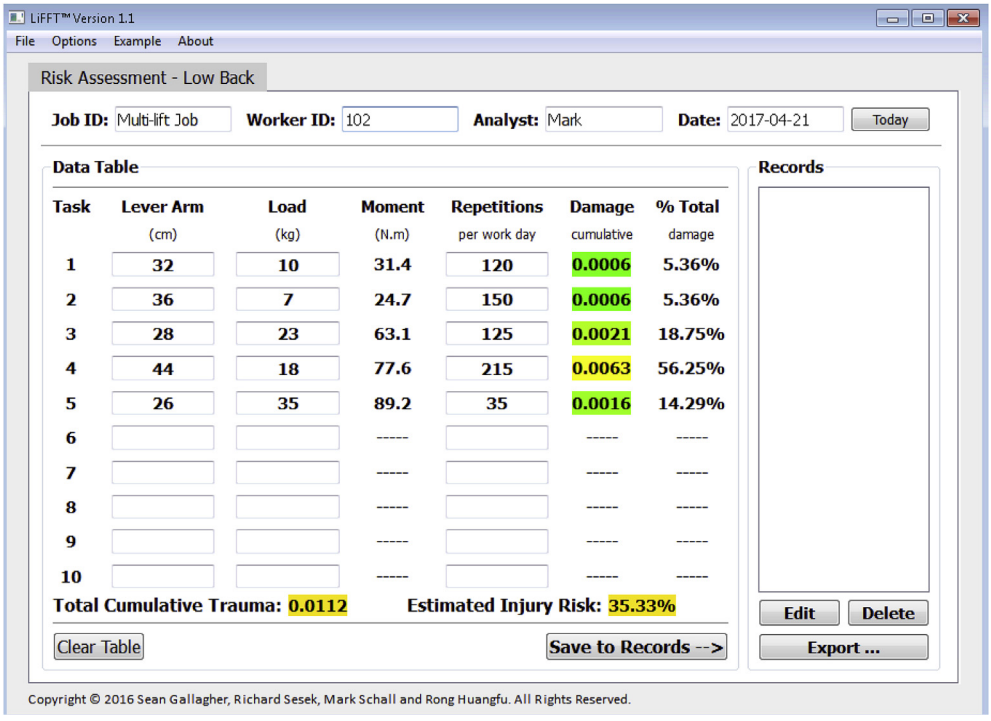

Fig. 4. Example of a multi-task lifting analysis using LiFFT. While individual tasks are generally low in risk, when summed the risk of LBP is moderate. Note that Task 4 accounts for approximately 56% of the cumulative load, and would be a prime target for redesign.

from the LMM database to validate the LiFFT risk assessment tool. For each of the 235 jobs in the database, the peak moment was associated with a value for DPC given the procedures described above. In the LMM database, Lifting Frequency is provided in lifts/hr, so this value was multiplied by eight to get an estimate of the daily dose of CD. Once the CD daily dose for each job was determined, data were arranged in ascending order of this variable. Data were then separated into deciles and counts of cases (jobs classified as high risk) versus total jobs were made for each decile. Binary logistic regression was used to determine significance of the model,

goodness of fit, and the deviance explained by the LiFFT CD measure (R^2_{DEV}), which is a maximum likelihood analogue to the coefficient of determination used in ordinary least squares models (Agresti, 1990). Estimates of LBD risk were developed based on the CD estimate from the tool. Odds ratios were used to examine whether differences were present among the various deciles of risk.

2.5. Validation using automotive epidemiology database (Sesek, 1999)

The automotive database consisted of data collected from six different plants. Only jobs with well-defined lifting activities were included (administrative jobs or jobs that did not have well defined tasks were not analyzed). Subject data used for this study was limited to reports of discomfort assessed by ratings of perceived discomfort and anonymized injury reports for the job on which the subject worked. Negative health outcomes were defined as self-reported LBP and LBP- related medical visits reported for the subject's job. Six different case/control definitions were explored. These definitions were a function of subject symptoms (on the day of interview or during the previous year and subject attribution of job relationship) and the presence or absence of one or more LBP-related medical visits reported for each subject's job in the previous year. Symptoms were categorized into one of five categories attributed to the job or to other jobs or factors: Category 1) "job related symptoms," symptoms originated on the subject's job; Category 2) "job aggravated," symptoms aggravated by the subject's current job, but not originating on job; Category 3) "no change or improvement in subject symptoms" while on the job, but symptoms not originating on the job; Category 4) "symptom improvement on the job," symptoms not originating on present job and improving; and Category 5) "no symptoms present." Symptoms were self-reported both on the day of the subject interview and retrospectively for the previous year. Case definitions included various combinations of symptoms and LBP-related injuries on the job in the previous year. Controls were subjects lacking job-related symptoms and/or working on jobs with no LBP-related reports of injury in the previous year.

While the LMM database consisted of jobs where workers performed the same job throughout the day, the automotive database contained numerous instances of jobs involving several different tasks (up to six), for which CD was calculated by summing the exposure calculated for each task. The PLM for each task was calculated by multiplying the horizontal distance to the load (measured according to RNLE method) and the known load mass. Repetitions for each task were available and were multiplied by the DPC to get the CD on a task basis.

A total of six separate low back case and control definitions were used in the automotive database. These included:

1) LBP *Today* (Categories 1 & 2) + Job Reported Injury (previous year) vs. No or Improving LBP (Categories 4 & 5) and no Job Related Injury (previous year)
2) LBP *in the Last Year* (Categories 1 & 2) + Job Related Injury (previous year) vs. No or Improving LBP (Categories 4 & 5) and no Job Related Injury (previous year)
3) LBP *Today* (Categories 1 & 2) vs. No LBP *Today* (Categories 4 & 5)
4) LBP *Today* (Category 1 only) vs. No LBP *Today* (Category 5 only)
5) LBP *in the Last Year* (Categories 1 & 2) vs. No LBP *in the Last Year* (Categories 4 & 5)
6) LBP *in the Last Year* (Category 1 only) vs. No LBP *in the Last Year* (Category 5 only)

As with the LMM database, once the total CD was obtained, data were sorted in ascending order of CD to perform logistic regression. Due to the lower number of cases for each outcome relative to the LMM database (averaging 53 versus the 111 for LMM database), the LiFFT CD measure was divided into quintiles for logistic regression analysis. As with the LMM database significance of the model, goodness of fit, and the deviance explained by the LiFFT CD measure (R^2_{DEV}) were assessed.

2.6. Validation using a LiFFT cut point for CD of 0.03

We were interested in determining if a specific cut point was effective at evaluating high risk vs. low risk tasks across both databases. Preliminary analyses indicated that a CD value of 0.03 would function as a cut point to discriminate between high risk and low risk jobs. Odds ratios, overall agreement, sensitivity, specificity, and both positive and negative predictive values were calculated for each measured outcome over both studies (one for LMM database and six for the Automotive database) using this cut point.

3. Validation results

3.1. Validation against the LMM database

Results of binary logistic regression analysis demonstrated that the CD estimate from LiFFT explained 92% of the deviance in LBDs in the LMM database (Zurada et al., 1997). Fig. 5 illustrates the fitted line and 95% confidence interval for the logistic regression. Odds ratios between deciles of CD are shown in Table 1. Fig. 6 provides the predicted LBD risk associated with CD estimates. As can be seen from this figure, there is a dose-response increase in LBD risk as CD estimates increase from 0.001 to 1.0.

3.2. Validation against the automotive epidemiology database

Fig. 7 illustrates binary logistic regression results for significant relationships between the LiFFT CD measure and LBP outcomes from the automotive database. The logistic regression for current LBP (1 vs 5) showed a significant relationship between CD and pain ($p = 0.013$), and this relationship explained 94.6% of the deviance in this relationship. Similarly, the logistic regression for current LBP (1/2 versus 4/5) as a function of the LiFFT CD was significant ($p = 0.029$) and explained 80.3% of the deviance. Further, analysis of the two outcomes involving LBP during the last year also demonstrated significant relationships to LiFFT CD estimates. For the outcome of LBP in the last year (5 vs 1), logistic regression demonstrated that the LiFFT CD was again significant (p = 0.029)

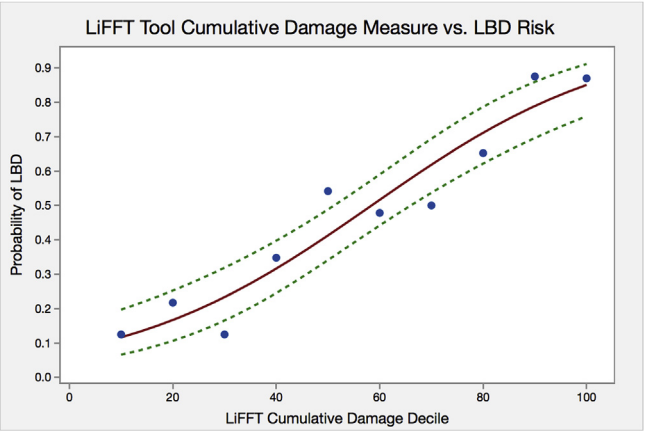

Fig. 5. Relationship between the LiFFT CD measure and the probability of LBD from the LMM database (Marras et al., 1993; Zurada et al., 1997).

Table 1
Odds ratios between deciles of risk per CD estimates for the LMM database (Marras et al., 1993; Zurada et al., 1997). Starred values represent risk deciles that are significantly different from one another.

		Cumulative Damage Deciles								
		20	30	40	50	60	70	80	90	100
Cumulative Damage Deciles	10	1.1 (0.2, 4.8)	0.7 (0.1, 3.6)	2.7 (0.7, 10.5)	3.6 (0.9, 13.7)	6.5* (1.7, 25.2)	4.2* (1.1, 16.2)	14.2* (3.4, 58.7)	25.0* (5.5, 114.1)	33.3* (6.6, 168.5)
	20		0.7 (0.1, 3.4)	2.5 (0.6, 10.0)	3.4 (0.9, 13.1)	6.2* (1.6, 24.0)	4.0* (1.0, 15.4)	13.5* (3.2, 55.9)	23.8* (5.2, 108.8)	31.7* (6.2, 160.5)
	30			3.7 (0.8, 16.5)	5.0* (1.2, 21.5)	9.1* (2.1, 39.3)	5.9* (1.4, 25.3)	19.8* (4.3, 91.3)	35.0* (6.9, 176.4)	46.7* (8.4, 258.9)
	40				1.3 (0.4, 4.4)	2.4 (0.7, 8.0)	1.6 (0.5, 5.1)	5.3* (1.5, 18.8)	9.4* (2.4, 37.1)	12.5* (2.8, 55.3)
	50					1.8 (0.6, 5.8)	1.2 (0.4, 3.7)	4.0* (1.2, 13.6)	7.0* (1.8, 26.9)	9.3* (2.2, 40.2)
	60						0.7 (0.2, 2.1)	2.2 (0.6, 7.6)	3.8 (1.0, 14.9)	5.1* (1.2, 22.2)
	70							3.3 (1.0, 11.4)	5.9* (1.5, 22.6)	7.9* (1.8, 33.8)
	80								1.8 (0.4, 7.3)	2.4 (0.5, 10.9)
	90									1.3 (0.3, 6.7)

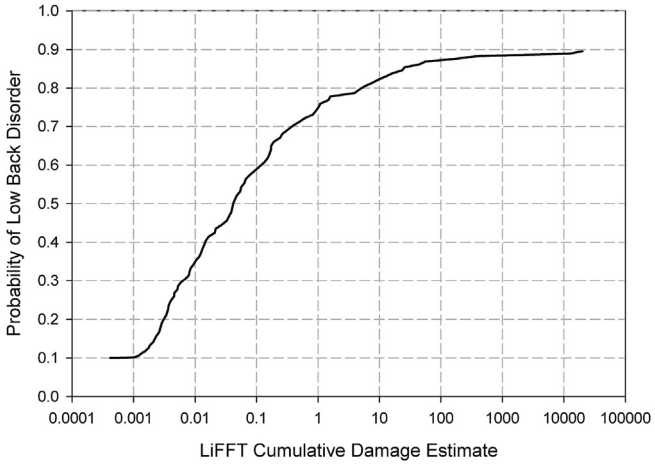

Fig. 6. Relationship between LiFFT CD measure and the risk of LBD derived from the LMM database (Marras et al., 1993; Zurada et al., 1997) analysis.

explained 88.5% of the deviance, and when examining LBP in the last year (5 vs 1), logistic regression was significant ($p = 0.046$) and explained 72.2% of the deviance. However, logistic regression results for the outcomes of LBP case + pain today (4/5 versus 1/2) and LBP + pain in the last year (4/5 versus 1/2) did not achieve significance in logistic regression analyses.

3.3. Analysis of a LiFFT CD cut point of 0.03

Table 2 provides the results of an analysis of the odds ratios, sensitivity, specificity, positive and negative predictive values and agreement for a LiFFT "daily dose" cut point of 0.03 for outcomes from both studies. As can be seen from this table, all LBP outcomes demonstrate significant odds ratios. Odds ratios were particularly strong for the case definitions of High Risk versus Low Risk group from the LMM database (OR = 9.50, 95% CI: 4.78, 19.18), and Injury Case plus Pain Today (OR = 9.65, 95% CI: 2.38, 39.15) and Injury Case plus Pain Last year (OR = 8.28, 95% CI: 2.60, 26.31). Each of the six case definitions from the automotive database demonstrated significant odds ratios with the CD measure, ranging between 2.80 and 9.65.

Overall, the cut point of 0.03 resulted in high agreement (71.5–86.8%), high specificity (0.90–0.96), high negative predictive values (0.67–0.90), but more modest positive predictive values (0.33–0.82). The highest positive predictive value (0.82) was observed for the measure of high versus low risk group membership from the LMM database; however, other positive predictive values were somewhat lower (0.36–0.53). Similarly, sensitivity was higher for the LMM outcome measure (0.50), but lower for outcome measures from the automotive study (0.16–0.31).

4. Discussion

We have presented a new risk assessment tool, LiFFT, for LBP/LBDs based upon fatigue failure principles. The tool has been designed to be easy to use and should be accessible to all safety and ergonomics practitioners (a Python 2.7 executable version it may be downloaded at http://eng.auburn.edu/oseoip). The only measurements required to use the tool are the load(s) being lifted, the maximum horizontal distance from the spine to the load, and a count (or estimate) of the number of daily repetitions. Extension of the tool to more complicated jobs that involve multiple tasks performed in a workday is quite easy and the "daily dose" of CD associated with LBP/LBD risk may be estimated by summing the individual subtask CD estimates. This provides an easy way to evaluate and compare risks associated with various tasks, and to determine priorities for job redesign.

The CD metric used by the tool demonstrated significant relationships for all LBP/LBD outcome measures in both epidemiological databases used for validation. Logistic regression of this measure against the LMM database outcome left only 8% of the deviance unexplained, and four outcome measures of LBP (both current and over the last year) in the automotive database explained between 72.3 and 94.6% of deviance. Two outcome measures in the automotive database (LBP case plus pain today or during the last year) did not demonstrate statistical significance in logistic regression; however, when examining a CD cut point of 0.03 both outcomes demonstrated substantial ORs (9.65 and 8.28, respectively).

Closer scrutiny of the data reveals the importance of the prevalence for specific outcomes and the strength of the relationship observed in logistic regression analyses. The outcomes involving LBP case + pain in the automotive database (current pain or pain in

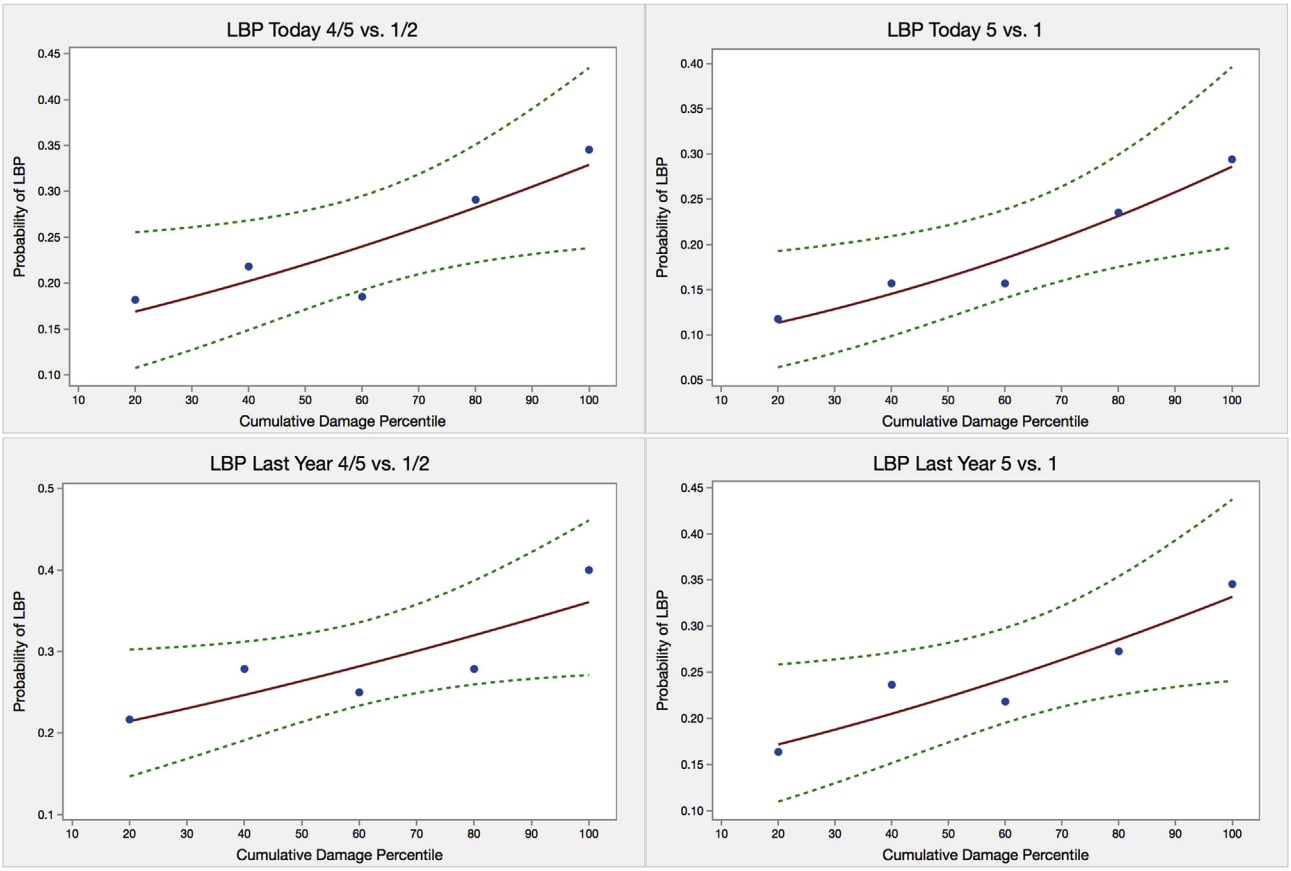

Fig. 7. Logistic regression results between the LiFFT CD measure and various LBP outcomes from the automotive database (Sesek, 1999).

Table 2
Results of the analysis for a LiFFT CD cut point of 0.03 for low back outcomes in both the LMM and Automotive Databases.

	Marras et al. (1993); Zurada et al. (1997)	(Sesek, 1999)					
	High Risk vs. Low Risk	Injury Case + Pain *Today* (4/5 vs. 1/2)	Injury Case + Pain in *Last Year* (4/5 vs. 1/2)	Pain *Today* (4/5 vs. 1/2)	Pain *Today* (5 vs. 1)	Pain *Last Year* (4/5 vs. 1/2)	Pain *Last Year* (5 vs. 1)
OR	9.50	9.65	8.28	2.80	2.91	2.81	2.94
95% CI	(4.71, 19.18)	(2.38, 39.15)	(2.60, 26.31)	(1.14, 6.87)	(1.09, 7.75)	(1.28, 6.17)	(1.29, 6.72)
Agreement	71.5	90.7	86.2	77.7	80.9	71.5	74.5
Prevalence	0.47	0.08	0.14	0.20	0.16	0.28	0.25
Sensitivity	0.50	0.31	0.28	0.17	0.18	0.16	0.18
Specificity	0.90	0.96	0.96	0.93	0.93	0.94	0.93
PPV	0.82	0.36	0.50	0.39	0.33	0.50	0.46
NPV	0.67	0.94	0.89	0.81	0.85	0.74	0.77
N	235	172	181	264	246	302	274

the last year) had very low prevalence rates (<14%), reflective of a small number of cases (22 and 26, respectively). The relative paucity of cases may explain why logistic regression failed to demonstrate significance for these outcomes, and why significant ORs for the CD measure were only observed in the cut point analysis. Outcomes involving pain had higher numbers of cases (49–86) and prevalence rates (ranging from 19 to 28%). A dose-response relationship between the LiFFT CD measure and outcomes emerged strongly and consistently for these cases. The LMM database outcome had by far the highest prevalence (47.2%) and demonstrated a very strong relationship to our CD measure, as mentioned above. The strength of relationship for the LBD outcome from this database may be due in part to the fact that low risk and high risk outcomes were separated by eliminating the medium risk category, making the relationship more pronounced. Additionally, the range of predicted CD was much wider for the LMM database.

One of the main benefits of the LiFFT risk assessment tool is that it is easy to calculate and understand how low back risk is influenced when multiple lifting tasks are performed. Other low back risk assessment methods either have no specific methods of combining the risk associated with multiple tasks, or use techniques that are computationally complex (e.g., NIOSH CLI). Further, the rationale for assessment of multi-task jobs for many previous techniques has been somewhat unclear. For example, the rationale

for assessment of the NIOSH CLI was that performing multiple lifting tasks would: 1) increase the physical or metabolic load and should result in a lower reduced RWL and increased LI, 2) increases in the LI depends upon the characteristics of the additional lifting task, and 3) that the increase in the LI due to the addition of one or more tasks is independent of preceding tasks. While these rationales appear reasonable, all are quite general and do not provide clear theoretical justification regarding how the incremental risk should be specifically quantified. LiFFT, on the other hand, provides a clear rationale for risk quantification of multiple lifting jobs. The CD associated with each task can be calculated by assessing the PLM and repetitions for each, and the CD for multiple tasks can be summed together as informed by validated fatigue failure techniques (Gallagher and Schall, 2016). The CD estimate provided by LiFFT for each individual task (or subtask) of a job provides unique information for development and/or selection of ergonomic interventions. Practitioners using LiFFT can quickly determine the specific aspect of a lift that would benefit the most from modification. The robust relationships observed between the CD calculated in this fashion and outcomes of LBP/LBDs provide considerable support for this method.

The fact that the LiFFT fatigue failure-based CD measure was significantly associated with all LBD/LBP outcomes across two separate epidemiology databases adds to increasingly compelling evidence that a fatigue failure process may be etiologically significant in the development of LBDs and LBP. Such a result makes sense as *all known materials fail by means of fatigue when loaded repetitively* (Ashby et al., 2013). This includes biomaterials associated with musculoskeletal disorders including lumbar motion segments (Brinckmann et al., 1988; Gallagher et al., 2005, 2007), tendons (Schechtman and Bader, 1997; Wang et al., 1995), ligaments (Thornton et al., 2007), bone (Carter and Caler, 1985), cartilage (Bellucci and Seedhom, 2001), and muscle (Gallagher et al., 2014). Animal models have demonstrated pathology congruent with fatigue failure theory (Barbe et al., 2013), including *in vivo* (Andarawis-Puri and Flatow, 2011). Further, epidemiology studies demonstrate a consistent interaction between force and repetition, indicative of a fatigue failure process (Gallagher and Heberger, 2013; Harris-Adamson et al., 2015). All signs suggest that MSDs are indeed the result of cumulative trauma, and that the theoretical basis used to predict cumulative damage development in materials (i.e., fatigue failure theory) performs extremely well in explaining injury risk.

Several caveats and limitations of LiFFT should be acknowledged. As with other lifting tools, it should be noted that specific risk estimates may not be protective for all workers. Fatigue failure theory suggests that relatively high loads may be acceptable for a limited number of exertions. While we believe this to be true, we advise caution for peak moments greater than 100 Nm. Estimates of percentage of gender representation in the labor force suggest that males comprised approximately 75% and women 25% of jobs involving materials handling (Gabriel and Schmitz, 2007), similar to the mix in the automotive database described above (Sesek, 1999). The current tool assumes that occupational lifting jobs are comprised in a similar manner. It should be apparent that ease of use was a priority in the design of this tool, and as such, other factors associated with LBP risk (such as trunk flexion) were not included. We examined inclusion of this factor; however, it was found not to significantly improve the association to LBP or LBD. This result may be due in part to the fact that increased PLM is often correlated with increased trunk flexion. Thus, PLM may already account for much of the variance associated with trunk flexion in the statistical models. Furthermore, while we strongly believe that factors such as age, gender, and anthropometry will influence MSD risk for specific individuals, inclusion of such factors in the current model was deemed to unnecessarily complicate a model that already explained risk well, and excluding such factors would help preserve practitioner usability.

Ultimately, prospective epidemiological studies will be required to determine whether a causal association exists between CD estimates derived from the LiFFT risk assessment tool with LBP outcomes. While it is extremely encouraging that the LiFFT CD measure validated well against LBP outcomes in two independent cross-sectional studies, additional research will clearly be necessary. Nonetheless, results suggest that fatigue failure methods show great promise in assessing MSD risk, and can be obtained in a manner quite accessible to practitioners with a minimum of training.

5. Conclusions

This paper describes an easy-to-use manual lifting risk assessment tool, “LiFFT”, that requires only the PLM (horizontal distance from spine to load times the weight of load) for a lifting task and number of repetitions performed for that task. A measure of CD is calculated based upon these values and can be summed across numerous tasks to derive a “daily dose” of CD. This measure was validated against two databases (Sesek, 1999; Zurada et al., 1997) and the following results were obtained:

1. The LiFFT CD measure explained 92% of the deviance with respect to LBDs in the LMM database (Zurada et al., 1997), consisting of mono-task jobs (i.e., jobs with no rotation).
2. Logistic regression models demonstrated significant relationships between our CD measure and outcomes involving both current LBP and LBP in the past year in an automotive manufacturer epidemiology study involving jobs where the risk associated with multiple tasks were summed. R^2 values for deviance ranged from 72 to 95%.
3. A cut point of 0.03 for the CD measure was found to result in significant odds ratios for all outcomes (i.e., both databases). Odds ratios ranged from 2.43 to 9.97.
4. Results strongly support the use of a CD measure (derived using fatigue failure techniques) to assess the risk of a wide variety of LBD/LBP outcomes.

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