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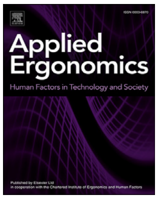

Development and validation of an easy-to-use risk assessment tool for cumulative low back loading: The Lifting Fatigue Failure Tool (LiFFT)

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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).

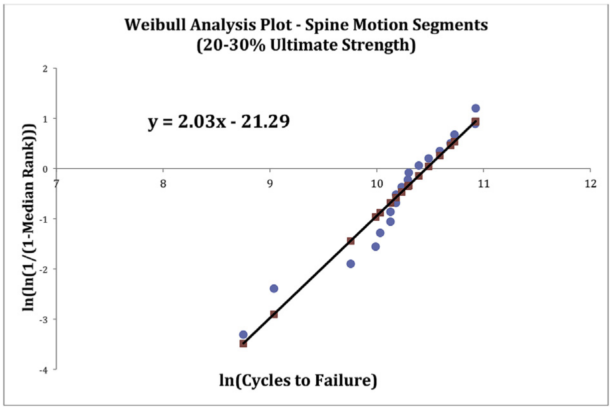

Fig. 1. A typical Weibull analysis for motion segments tested at 20–30% of the spine's Ultimate Stress (US). The horizontal scale of the Weibull data plot displays the log fatigue life, while the vertical scale represents the cumulative percentage of failures. Blue circles represent the combined data 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. 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:

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

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.

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

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

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