UTILIZING FATIGUE FAILURE THEORY TO RELATE LOW BACK LOADING TO PREDICTED SPINAL STRENGTH: UPDATE ON THE LOW BACK CUMULATIVE TRAUMA INDEX

Yousif Abulhassan, MISE, AEP, Menekse Salar, MISE,
Muhammet Capanoglu, MISE, Janson Webb, Sean Gallagher, PhD, CPE
Department of Industrial & Systems Engineering
Auburn University

The purpose of this study is to develop a model to determine the effects of personal characteristics (age, gender, height and weight) and work activities (lifting, twisting and bending) in the development of low back pain (LBP). Accordingly, the proposed model is developed using fatigue failure theory as a basis to evaluate trauma as was demonstrated by Gallagher & Sesek (2014), with the dose-response relationship between the low back cumulative index (LBCTI) and low back disorders (LBD). 3D Static Strength Prediction Program (3DSSPP) was used to collect data and to generate L4/L5 compression force. Additionally, a questionnaire was developed to gather demographic data from workers and task-related data. In order to utilize these inputs, a user-friendly ergonomic assessment application was formulated to allow a worker to easily input the factors related to their job, and to obtain results determining the risk of developing low back pain.

INTRODUCTION

Low back disorders (LBD) are one of the most common and costly Musculoskeletal Disorders (MSD) in industry (Marras et al., 1999a). After headaches and tiredness, back pain is the third most common health problem reported by individuals (Waddell, 1999). The American Society of Orthopedic Surgeons has identified Low Back Disorders (LBD) as one of the most frequently reported and costly medical problems facing society today (Praemer et al.,1999). LBD is also one of the major contributors to musculoskeletal disorders experienced by industry [Marras et al., 1995]. In addition to the loss of work time, LBDs place a significant burden on society, with an average incident estimated to be over $30,000 (Ohio Bureau of Workers Compensation 1994) [Marras et al., 1995]. Identifying the causes of LBD is difficult because it can be due to a combination of working conditions and activities that occur beyond the workplace. Recent publications in "Theoretical Issues in Ergonomics Science" have discussed the importance of cumulative spinal loading and a need to develop models capable of accounting for cumulative stress in the spine from manual material handling (MMH) (Merryweather et al., 2008).

To help identify jobs with an elevated risk of causing LBDs, researchers have developed specific tools and measurement methods (Marras et al., 1999b). Current ergonomic tools attempt to assess the risks of LBD as a result of various manual material handling jobs using common MSD risk factors: force, repetition, posture and vibration. One of the main issues with the current models is that workers tend to experience highly variable load exposures, the cumulative effects of which are not well handled by current tools. However, recent evidence has suggested that repetitions with high force has a greater impact on the risk of developing LBD compared to cycles consisting of low force (Gallagher & Heberger, 2013;Coenen, et al., 2012; Brinckmann et al., 1988). According to Gallagher and Heberger (2013), the fatigue failure theory would suggest that force and repetition are not independent risk factors for low back disorders and that the interaction between them should be taken into consideration when calculating the cumulative trauma experienced by the tissues. Using fatigue failure theory provides a method to assess cumulative trauma for tasks that involve variable loading and repetition exposures. Current tools (traditional, static, or biomechanical) often focus on single load exposures, and treat force and repetition as independent MSD risk factors. However, workers often experience highly variable load exposures and utilizing a single load exposure may affect the accuracy of the results from current ergonomics assessment tools.

Fatigue failure theory can provide a more accurate assessment of MSDs by utilizing variable loading patterns (Gallagher & Heberger, 2013). Implementing fatigue failure theory could result in better job rotation schemes, greater identification of high MSD-related tasks, and help individualize risk assessment based on personal factors (age, gender, health, etc.) This paper serves as an extension on developing the LBCTI research conducted by Gallagher and Sesek (2014).

BACKGROUND

Most MSDs that occur in the workforce are the result of the cumulative effects of smaller amplitude forces that occur during repetitive tasks and movements (Barbe & Gallagher et al., 2013). Repetitive motion, non-neutral body postures and forceful exertions are key risk factors for the occurrence of MSDs (Barbe & Gallagher et al., 2013). Force and repetition have generally been considered as independent major risk factors in MSD development (Gallagher & Heberger, 2013). Current ergonomic assessment tools related to the low back region such as the American Conference of Industrial Hygienists Threshold Limit Values (ACGIH TLV), NIOSH Lifting Equation, Rapid Upper Limb Assessment (RULA), and Rapid Entire Body Assessment (REBA) do not consider any personal characteristics or implications of fatigue failure theory. By incorporating fatigue failure theory in ergonomic assessment, the interaction between force and repetition is taken into consideration by assessing MSDs utilizing variable load patterns. The interaction between the MSD risk factors, force and repetition was observed in 10 out of 12 studies reviewed by Gallagher & Heberger, 2013. Figure 1 plots data derived from seven cross-sectional studies that broke down low back MSD risks into four quadrants: low force, low repetition (LFLR); low force, high repetition (LFHR); high force, low repetition (HFLR); and high force, high repetition (HFHR) (Gallagher & Heberger, 2013).

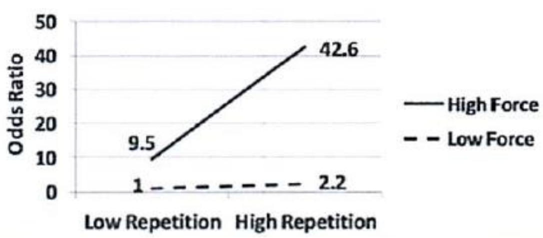

Figure 1 – Effects of force and frequency on risk of low back disorders (Marras et al., 1993 data as reported by Zurada et. al. 1997)

The main observation presented in Figure 1 is the difference in slopes for the Low/High Force lines. Low force activities have a low to mild risk factor whereas the high force activities have a substantial risk as the repetitions increase (Gallagher & Heberger, 2013). A common finding with many of the studies was that of the HFHR condition being the only condition found to be significantly different from that of the LFLR group (Gallagher & Heberger, 2013).

With respect to interaction of force and repetition in biological materials, a very limited number of fatigue failure studies have been performed. The majority of those studies tend to result in the complete destruction of the tissue when relating the force and repetition interaction with fatigue failure (Brinkmann et al., 1988; Schechtman & Bader, 2002). However, "MSDs are usually not characterized by complete rupture of a tissue but are instead characterized by a lower-magnitude, localized tissues damage sufficient to trigger an inflammatory response" (Gallagher & Heberger, 2013). In many materials, there is a fatigue limit to which the material may experience repeated loading that will not lead to a failure (usually around 30% of the materials ultimate stress).

As current LBD assessment tools have not considered a fatigue failure-based model of cumulative trauma development, the purpose of the current paper is to describe the development of a LBD risk assessment tool that incorporates fatigue failure theory principles to assess risk.

METHODS

Development of the Tool/Data Collection

The tool conception was to evaluate risk to a worker performing assembly line tasks, and provided the ability to assess jobs where workers would rotate through different tasks throughout the workday. Variables used to assess manual lifting task risk included individual characteristics (age, gender, anthropometric percentile), and task related variables (trunk flexion, trunk rotation, upper arm angle, elbow angle, load weight, duration of task, cycles per minute, and rest time).

Data Analysis

The 3DSSPP biomechanics model (University of Michigan, 2012) was used to generate L4/L5 compressive force data for males and females at the 5th, 50th, and 95th percentiles (3DSSPP Model). Compressive data was generated for lifting objects weighing between 10 and 70 pounds (10 pound increments), at each combination of angles shown in Table 1. A total of 15,361 combinations were extracted from the 3DSSPP model.

Table 1 – Combination of body angles used in 3DSSPP

Trunk Flexion	Trunk Rotation	Upper Arm Angle	Elbow Angle
30, 45, 60, 75, 90 (Neutral)	**0 (Neutral), 15, 30, 45**	**0, 30, 60, 90**	**0, 30, 60, 90**

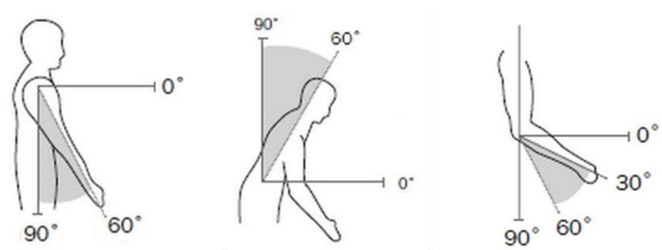

Figure 2 – Body Segment Angle Representation

Ultimate strength data of the lumbar spine for males and females between the ages of 20 and 60 years old was used to calculate the percentage of ultimate compressive strength experienced by the lumbar spine for a specific manual material handling scenario. As shown in Table 2, the ultimate strength provided was the average ultimate strength of the lumbar spine of four age groups, and the ultimate strength at ±1 standard deviations (Jäger and Luttmann, 1991). The percentage of ultimate compressive force was measured using the average ultimate compressive force for a 50th percentile person, a 95th percentile person, and a 5th percentile person.

A recent paper (Gallagher et. al., 2014) used Weibull analysis to relate the percentage of ultimate strength of the spine to the amount of damage that would be experienced by the spine using data from Brinckmann et al. (1988) and

Gallagher et al. (2005). This analysis was used as the basis to determine the percentage of damage experienced by the spine resulting from compression experienced in various manual lifting tasks. However, it was observed that when biomechanical estimates of compression were calculated and compared to predicted spine ultimate strengths given by Jäger and Luttmann (1991), estimates of the rate of cumulative trauma development appeared excessive. This may be due to several reasons. For example, the ultimate strengths of cadaver spines were measured *in vitro*, therefore not necessarily representing the ultimate strength of the spine in vivo due to various *in vivo* characteristics. In addition, the precise accuracy of spinal compression estimates derived from biomechanical models is not known. To address this excessive rate of predicted cumulative trauma development, the cycles to failure data resulting from a cyclic loading at specific percentages of ultimate strength reported by Brinckmann et al (1988) and Gallagher et al. (2005) were (arbitrarily) multiplied by two.

Five risk levels were developed for the percentage of ultimate compressive strength, which was based on the amount of damage experienced per cycle at the levels of ultimate compressive strength as illustrated in Table 3.

Table 2 – Ultimate Strength of the Lumbar Spine by Age and Gender (Newtons) (Jäger and Luttmann, 1991)

		20-30 years	30-40 years	40-50 years	50-60 year
Males	Mean + 1 SD	10600	10400	8400	7200
	Mean	7800	7700	6000	5000
	Mean – 1 SD	5000	5000	3600	2800
Females	Mean + 1 SD	7000	6900	6300	5100
	Mean	5900	5400	4700	3600
	Mean – 1 SD	4800	3900	3100	2100

Table 3 – Risk Levels

Risk Level	Percentage of UCS	Damage/Cycle
Low	0 - 18%	0 - 0.000899%
Medium Low	19 - 37%	0.001016 - 0.00913%
Medium	38 - 56%	0.01013 - 0.092704%
Medium High	57 - 75%	0.10473 - 0.9414 %
High	76 - 100%	1.0636 - 19.8788%

Application Development

Microsoft Excel© was used to develop the ergonomic assessment tool. A user-friendly interface was developed input data specific to the worker and task. The tool is designed to evaluate a task at the worst posture experienced during a lifting task. In addition to the damage experienced per cycle, the total damage resulting from performing the task over time is also calculated using the duration of the task and the number of cycles performed per minute.

The raw data of the tool is divided into three sections: 3DSSPP data, ultimate strength data, and the damage per cycle data. The age and gender inputs from the user are used to lookup the ultimate strength of the lumbar spine by using an index and match function. Body segment angles and the percentile of the worker are used to lookup the L4/L5 compressive strength resulting from the task. The tool is setup to calculate the percentage of ultimate strength by dividing the compressive strength obtained from the 3DSSPP data by the ultimate compressive strength. Another lookup function is used to match the percentage of ultimate strength to the amount of damage estimated to be experienced per cycle. An approximation was used to round the percentage value to match one of the given percentage values in the damage per cycle data. The user also has the option to calculate the damage experienced per task by inputting the duration of the task and number of cycles experienced per minute.

Rest/Cumulative Damage Ratio

Work/rest schedules have been studied and findings show that rest times help to prevent the accumulation of excessive fatigue failure (Shin & Kim, 2007). According to some studies, inadequate or short amount of break times can lead some serious diseases/disorders such as debilitating and cumulative neuromuscular disorder (Fransen et al., 2002; Solomonow, 2004; Hoops et al., 2007; Sbriccoli et al., 2007). It is the belief of the authors that the rest required to heal damaged tissues is related to the magnitude of cumulative damage incurred (i.e., higher damage requires greater healing time). Thus, a metric was created to evaluate this relationship. The following equations were used to measure the rest/cumulative trauma ratio:

Cycles per task = duration of task x cycles per min. (1)

Rest per task = duration of task – (duration of cycle/60 x cycles per task) (2)

Cumulative damage = total damage / total cycle (3)

Rest/Cumulative Trauma Ratio = Rest per Task (hrs)/Cumulative Damage (4)

Total Workday Cumulative Trauma Assessment

Total damage per workday is calculated by adding the total damage experienced per task. Total rest times in a workday are then inputted into the tool to get an estimate of the overall damage experienced to the total amount of rest per workday as shown in Table 4.

Table 4 – Sample results of a total workday assessment

	Task 1	Task 2	Task 3	Task 4
Duration of Task (minutes)	120	120	120	120
Damage Per Task	72.14%	3.02%	0.30%	0.89%
Rest Per Task (Minutes)	90	90	90	90
Rest/Cum. Trauma Ratio	2	50	504	168

Ergonomic Assessment using the LBCTI

The following steps are followed to assess a task:

1. The workers personal characteristics are recorded (gender, age, percentile). This information is used to determine the ultimate compressive strength of the workers spine and to determine the anthropometrics of the worker in the 3DSSPP database.
2. Upper extremity angles of the worker are measured when the worker is at the worst posture (deviated from neutral posture) while performing the task.
3. The duration of the task, duration of the cycle, total break time, and the number of cycles per minute are also recorded to determine the rest to work ratio of the task.
4. After the previously mentioned information is inputted into the LBCTI tool, the tool will provide the evaluator with the compression experienced by the workers spine, the number of cycles that would theoretically cause the spine to fail, and the amount of damage experienced per cycle.
5. The evaluator also has the option to archive the results for several tasks, and determine the total damage experienced by the spine in an entire shift.

Sample Tasks using the LBCTI

A mock-up job consisting of four tasks was developed to evaluate the tool. The four tasks consisted of lifting light to heavy objects using different postures as detailed in Table 5. It was assumed that the worker performs three cycles per minute, and the duration of each cycle is five seconds.

Table 5 – Tool input information

	Gender	Age	Percentile	Trunk Flexion	Trunk Rotation	Upper Arm Angle	Elbow Angle	Load Weight
Task #1	Male	28	50	90	15	60	60	45
Task #2	Male	28	50	30	15	90	90	30
Task #3	Male	28	50	60	15	90	30	15
Task #4	Male	28	50	90	15	60	60	45

The results obtained from the LBCTI for the four sample tasks are illustrated in Table 6. The damage per task increases as the load weight increases and the body deviates from neutral posture.

Table 6 – Mock-up job assessment results

	Task 1	Task 2	Task 3	Task 4
Duration of Task (minutes)	120	120	120	120
Damage Per Task	0.89%	3.02%	0.43%	0.89%
Rest Per Task (Minutes)	90	90	90	90
Rest/Cum. Trauma Ratio	168	50	349	168

RESULTS

The low back cumulative trauma index provides the following outputs: 1. Damage per cycle; 2. Cycles to Failure; 3. Damage per task; 4. Rest/cumulative trauma ratio; 5. Total damage per workday. When using the tool to assess the ergonomic hazards of a job, an ergonomist would need the following inputs at the worst posture during a lift: gender, age, percentile, trunk flexion, trunk rotation, upper arm angle, elbow angle, and load weight. Additionally, the tool allows an ergonomist to archive the results obtained from the tool for each worker assessed. Sample Results from the tool are shown in Table 7 and Table 8.

Table 7 – Sample results for one shift

Low Back Cumulative Trauma Index Tool Results			
L4/L5 Compression	Percentage of UCS	Cycles to Failure	Damage Per Cycle
577.79	32.95%	20,161	0.005%

Table 8 – Sample results for a total workday

Worker 1	Task 1	Task 2	Task 3	Task 4
Duration of Task (Min)	120	120	120	120
Damage Per Task	0.89%	3.02%	0.43%	0.89%
Rest Per Task (Min)	90	90	90	90
Rest/Cumulative Trauma Ratio	168	50	349	168
Total Damage Per Workday	5.24%			

DISCUSSION

The purpose of the LBCTI tool was to have the means to incorporate a fatigue failure model in defining the effects of manual material handling tasks on the low back. Previous ergonomic assessment tools have not incorporated the concept of fatigue failure. The previous tools are important in identifying high-risk jobs, however they tend to focus on single load exposures as well as treat force and repetition as independent MSD risk factors. As mentioned previously, using the fatigue failure theory can provide a method to assess low back MSDs utilizing variable loading patterns and thus lead to greater identification of high MSD related tasks and help to individualize risk assessment based on personal factors. With the LBCTI model, load exposures can be varied with different anthropometric inputs over various cycle/task durations. This data can then be used to develop better job rotations in the workforce and assist to develop more productive rest / healing periods.

Pertinent information in regards to manual material handling (age, gender, job task description) was obtained with a questionnaire and the specific jobs tasks were analyzed by direct observation. The questionnaire consisted of task-related questions answered by the observer as well as worker-related questions. In addition to this, the overall data generated from 3DSSPP is based on a biomechanics model, which has some limitations such as assuming rigid body segments and disregard the loading behavior of viscoelastic materials. Ultimate strength data was used from the Jäger and Luttmann (1991) analysis. This study used cadaver spines, which have different strength properties and behave differently when compared with living human beings' low back anatomy. While those limitations may not provide an accurate amount of damage resulting from performing a task, they are able to provide the relationship of fatigue failure by rating high forces at a much higher damage compared to low forces.

Previous ergonomic assessment tools such as the ACGIH values (Threshold Limit Values for Chemical Substances and Physical Agents) are useful in determining the acceptable threshold limit for lifting task but do not differentiate lifting limits with respect to gender, age, or anthropometry. The tool recently developed evaluates the task at the expected posture to be experienced and calculates the damage experience per cycle and the total damage resulting from performing the task over the task by using the duration of the task and the number of cycles conducted per minute. The PLIBEL tool, developed with the assistance of Marras, was designed to standardize a practical method for identifying ergonomic hazards in the workplace. However, PLIBEL did not include any duration criterion it its assessment and is not generally intended for any specific occupations or tasks. The NIOSH Lifting Equation assesses the risk of LBD in the workforce and is based off various biomechanical, psychophysical, and physiological criteria. While the NIOSH Lifting Equation is a good measure to assess risk levels of MMH for LBD, it does not account for lifting/lowering for over 8 hours or rest periods that the worker would take. These limitations of the NIOSH Lifting Equation are rather common in today's workforce, which is why we incorporated inputs for the duration of the tasks and rest periods in the calculation for the damage experience per cycle.

Raw data for the tool was divided into three sections: 3DSSPP data, ultimate strength data, and the damage per cycle data. The 3DSSPP model was utilized to generate L4/L5 compressing force data for males / females of three different percentiles (5^{th}, 50^{th}, and 95th). The ultimate strength data of the lumbar spine for males/females between the ages of 20 – 60 years of age were then utilize calculate the ultimate compressive strength of specific activities and the damage resulting from a single cycle of that activity. The range of age from 20 – 60 years is a sufficient representation of the majority of the workforce, however our model could have utilized a greater range of anthropometry.

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