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Development and validation of a cumulative exposure shoulder risk assessment tool based on fatigue failure theory

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ABSTRACT

Objective: To present a new risk assessment tool for shoulder intensive occupational tasks based on fatigue failure theory.

Methods: The tool estimates cumulative damage (CD) based on shoulder moments and loading cycles using an S–N curve derived from in vitro tendon fatigue failure tests. If multiple shoulder tasks are performed, the CD for each is summed. In the validation, 293 workers were evaluated for five separate shoulder outcomes. Logistic regression was used to assess the log CD against five shoulder outcomes adjusted for covariates including age, sex, body mass index (BMI), and plant site.

Results: Both crude and adjusted logistic regression results demonstrated strong dose-response associations between the log CD measure and all five shoulder outcomes (continuous ORs ranged from 2.12 to 5.20).

Conclusions: The CD measure of The Shoulder Tool demonstrated dose-response relationships with multiple health outcomes. This provides further support that MSDs may be the result of a fatigue failure process.

Practitioner summary: This study presents a new, easy-to-use risk assessment tool for occupational tasks involving stressful shoulder exertions. The tool is based on fatigue failure theory. The tool was tested against an existing epidemiology study and demonstrated strong relationships to multiple shoulder outcomes.

Abbreviations: MSD: musculoskeletal disorder; NORA: national occupational research agenda; RULA: rapid upper limb assessment; REBA: rapid entire body assessment; S-N: stress-number of cycles; EDL: extensor digitorum longus; DPC: damage per cycle; CD: cumulative damage; UTS: ultimate tensile strength; FTOV: first time office visit; 3DSSPP: 3-dimensional static strength prediction program; AS: visual analogue scale; BMI: body mass index; CI: confidence interval; Nm: newton-metre; LiFFT: lifting fatigue failure tool; DUET: distal upper extremity tool; OMNI-RES: OMNI resistance exercise scale.

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KEYWORDS
Musculoskeletal disorders; fatigue failure theory; risk assessment and management; concurrent validation; shoulder

1. Introduction

MSDs are common and costly adverse health conditions that represent the largest category of occupational injuries across the United States. MSDs account for approximately one-third of occupational illnesses and injuries requiring days away from work (Bureau of Labor Statistics 2015). Indirect and direct costs resulting from MSDs in the U.S. are extremely large, with $100 billion expended per year on indirect costs and $20 billion spent on direct costs including workers' compensation (Occupational Safety and Health Administration 2014). Occupational lost time claims for upper extremity injuries, including shoulder injuries, are ranked second highest after back injuries (Brookham, Wong, and Dickerson 2010). A recent study of shoulder complaints in the working adult population has demonstrated shoulder symptoms in approximately 30% of surveyed subjects (Herin et al. 2012). In 2014, 88,980 non-fatal shoulder injuries and illnesses occurred that involved days away from work causing a median of 26 days of lost work with the longest absences compared to any other body part (Bureau of Labor Statistics 2014). Shoulder pain is the third most common complaint leading to musculoskeletal related primary care consultation in the United States (Mitchell et al. 2005; Linaker and Walker-Bone 2015).

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Risk factors associated with the development of MSDs include physical stress, psychosocial stress, and individual characteristics. Several physical risk factors have been observed to be associated with shoulder pain, including forceful exertions, heavy loads, working with elevated arms, exposure to vibration either from tools or machines, and repetitive motions. Psychosocial risk factors include, but are not limited to, social support at work, job demands, and job control (Linaker and Walker-Bone 2015; Van Der Windt et al. 2000; Hanvold et al. 2015; Pribicevic 2012; Shanahan and Sladek 2011; Kiss et al. 2012; Larsson, Søgaard, and Rosendal 2007; Van Rijn et al. 2010; Pope et al. 1997; Bongers, Kremer, and Laak 2002; Andersen et al. 2002, 2003; De Zwart, Frings-Dresen, and Kilbom 2000). Individual risk factors (including personal characteristics) also have been shown to play a role in shoulder MSD development (Andersen et al. 2002). Moreover, interactions among these factors have been observed to influence the incidence of MSDs (Harris-Adamson et al. 2015).

Cumulative loading is widely believed to be a major contributing factor for the development of MSDs (Norman et al. 1998; Callaghan, Howarth, and Beach 2011). Several studies have suggested methods for addressing cumulative loading where the cumulative damage (CD) for the total job is estimated by considering each individual task. Such studies, for instance, have considered measures such as peak spinal load, task duration, task frequency, loading during rest time, total rest time, and number of tasks performed (Norman et al. 1998; Callaghan, Howarth, and Beach 2011). However, most of these studies have used linear integration methods, which assume that low force, long duration and high force, short duration tasks have the same injury risk (Norman et al. 1998; Callaghan, Howarth, and Beach 2011). Other studies have shown that force increases are more detrimental for the development of MSDs when compared to increased exposure time (Jäger et al. 2000).

Several studies have demonstrated that biological tissues exhibit an interaction between the risk factors of force and repetition, in a pattern anticipated by fatigue failure theory (Barbe et al. 2013; Gallagher and Heberger 2013). For example, tendon, cartilage, and bone pathology as well as cytokine responses, have all revealed an interaction pattern of force-repetition suggestive of a fatigue failure process in a novel rat model examining upper extremity pulling tasks (Barbe et al. 2013). The interaction of force and repetition in the development of MSDs was also investigated in a systematic review of epidemiological studies where correspondence with the fatigue failure process was demonstrated. In the study, many MSDs exhibited the pattern anticipated by fatigue failure including tendinitis, epicondylitis, carpal tunnel syndrome, low back disorders and hand pain (Gallagher and Heberger 2013). Tissue loading in animal studies, epidemiological studies, and in vitro fatigue testing of musculoskeletal tissues all provide further evidence supporting a fatigue failure process in the development of MSDs (Gallagher et al. 2018). This suggests that cumulative loading effects may be estimated by using fatigue failure methods.

The exposure-response relationship between shoulder pain and workplace risk factors is still unclear, and associations are not well understood (Van Der Windt et al. 2000). However, the public health burden of shoulder pain highlights the need to develop models and exposure assessment tools to predict the risk of shoulder injuries and implement prevention strategies. The third decade of the National Occupational Research Agenda (NORA) highlighted the need to understand the risk factors for work-related MSDs and to improve methods for exposure assessment and develop new risk assessment models and methods (National Occupational Research Agenda for Musculoskeletal Health 2019).

Current observational tools available for shoulder joint assessment (e.g. Rapid Upper Limb Assessment (RULA) (McAtamney and Corlett 1993), Rapid Entire Body Assessment (REBA) (Hignett and McAtamney 2000) do not consider the effect of cumulative loading on MSD risk. In addition, evaluation of jobs comprised of multiple tasks and their combined effects are also not available (Janowitz et al. 2006; Takala et al. 2010). This highlights the need for a new tool that can be used to estimate CD development in the shoulder. To maximise utility and increase the likelihood of use by practitioners, such a tool should also be user friendly.

This article introduces a new shoulder risk assessment tool ("The Shoulder Tool") based on the principles of fatigue failure theory. This paper describes the development of the tool, explains how it may be applied to estimate cumulative loading for both monotask and multitask jobs, and provides a concurrent criterion-related validation of the resulting CD metric against an existing epidemiological study database. A risk model is provided based on the validation results of the shoulder tool.

2. Methods

2.1. Model logic

Fatigue failure theory suggests that all materials accumulate damage as they are repeatedly loaded and unloaded below their ultimate strength. This process may ultimately lead to failure. An exponential relationship exists between the stress magnitude and number of cycles to failure. This pattern of failure has been observed in animal tissue loading studies, epidemiological studies, and in vitro fatigue testing of musculoskeletal tissues (Gallagher et al. 2018; Schechtman and Bader 1997). Tendons of the shoulder are musculoskeletal tissues of particular concern (Dickerson, McDonald, and Chopp-Hurley 2020). In developing a cumulative damage model, it is a recommended practice to employ actual fatigue testing data from the type of material being modelled (Stephens et al. 2001). Thus, data from a study by Schechtman and Bader (Schechtman and Bader 1997), which developed a "stress-life" (S–N) curve for human tendons was utilised. In this study, ninety specimens of the human extensor digitorum longus (EDL) tendon were tested using 10 specimens at nine different stress levels. Cyclic square tension-tension stress with physiological frequencies were employed in the study. Equation (1) describes the exponential relationship between the applied stress and median fatigue life (50% probability of failure) for the EDL from which the damage per cycle (DPC) can be estimated at a certain stress level:

$$S = 101.25 - 14.83\ \log(N) \quad (1)$$

where S is the normalised stress as a percentage of the ultimate tensile strength (UTS), and N is number of cycles to failure (Schechtman and Bader 1997). DPC for various levels of stress is an important factor for the shoulder tool development and is derived by dividing 1 by the number of cycles to failure at a particular level of stress. The CD incurred in a job can be estimated using Equation (2). Summation of the multiplication of the DPC and the repetitions for each task can be used to give an estimate for the daily dose of CD when a worker is performing multiple tasks. Equation (2) shows how the daily dose is derived for CD:

$$Total\ CD = \sum_{i=1}^{j} DPC_i \times n_i \quad (2)$$

where *Total CD* is the daily dose for the CD for all tasks, DPC_i is the damage per cycle for task i, i is number of tasks in a job with a total of j tasks, n_i is the number of repetitions within task i (Gallagher et al. 2018).

2.2. Exposure assessment

The epidemiology study used to develop and validate The Shoulder Tool was approved by both the University of Utah and the University of South Florida Institutional Review Boards. Subjects signed consent forms prior to participation. Those who had been on a cyclic job for more than 30 days and agreed to be filmed were included in the study. The epidemiology study was executed in six different plant sites of a large US automotive manufacturer over the period of February 1998 to September 1999 (Sesek 1999). A total of 1022 subjects participated with male subjects representing 72.7% of the workforce. The age range was 20–70 years (41.0 ± 10.9 years SD). Subject heights ranged from 147 to 203 cm (174.8 ± 9.4 cm SD), and the weight range was between 45 and 159 kg (84.8 ± 17.7 kg SD).

The database in the study included injury records as well as self-reported symptoms. Injury history records and symptoms for different body parts based on an interview and structured questionnaires were included in the database. A visual analog scale was included in the questionnaire for subjects to rate pain for different parts of the body including the shoulder. First Time Office Visits (FTOVs) for shoulder/neck symptoms were also reported. Self-reported pain symptoms were recorded on the day of the interview and retrospectively for the previous year. In addition, attribution of the job and its relationship to reported pain/injury was recorded. It is important to note that when multiple workers completed the same job, the subject reporting the injury was not necessarily the same subject observed during exposure assessment.

Figure 1 illustrates the flow chart for the development of The Shoulder Tool. Repetitions per workday for each task and postural estimates were inputs. Two hundred sixteen randomly selected jobs were included in the analysis, which consisted of a total of 446 tasks. Jobs analysed were generally multitask in nature, with up to six tasks per job. Task descriptions for each job were available from the epidemiology dataset. Video analysis was used to obtain postural estimates and the number of repetitions by measuring the duration between the start of a cycle of a job to the start of the subsequent cycle.

The most awkward shoulder posture for a task was used for postural analysis where the neutral posture was defined as arms hanging straight down by the side of the torso. Determination of the most awkward postures observed was based on the epidemiological evidence that repeated or sustained postures $>60°$ for flexion and abduction contribute to the development

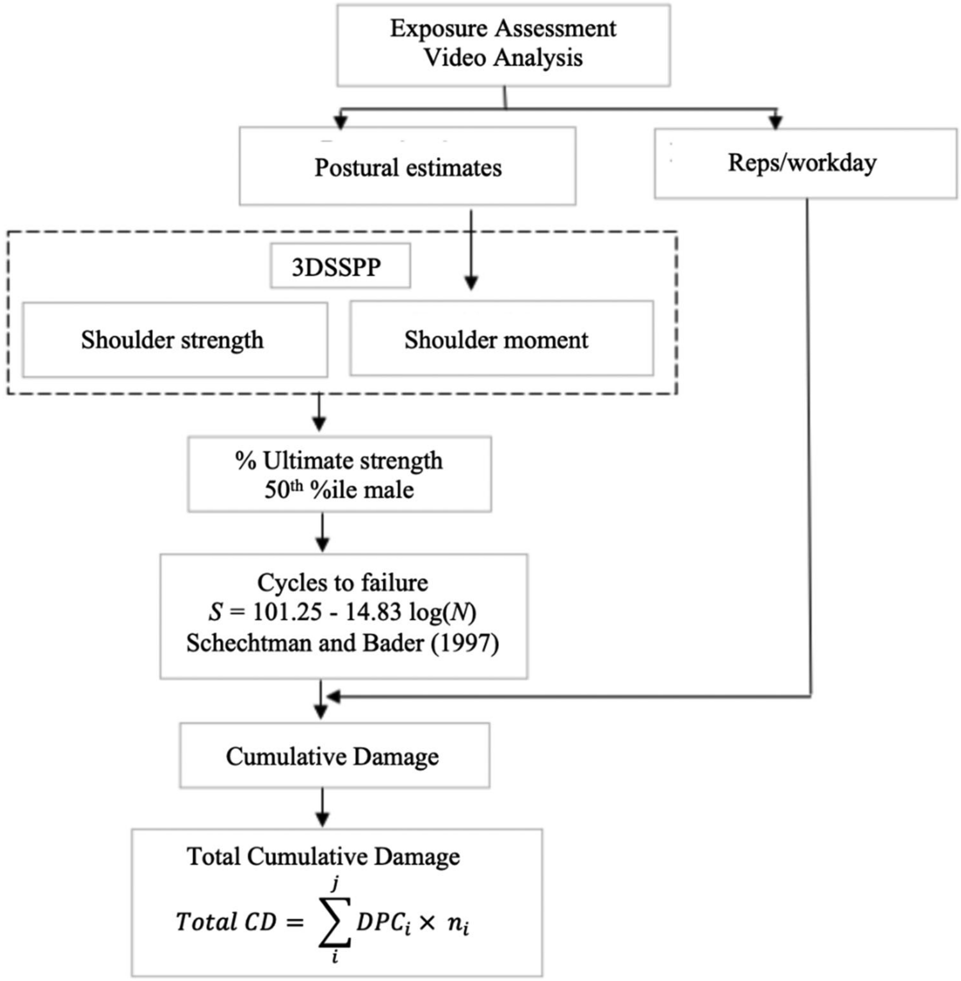


Figure 1. A flowchart of the development process for The Shoulder Tool.

of shoulder MSDs (Bernard and Putz-Anderson 1997). Angles of 60°–120° of arm elevation have been observed to increase mechanical pressure from the acromion on the supraspinatus tendon, and angles of 45°–90° of shoulder flexion and abduction have been observed to increase muscle activity of the deltoid that has been associated with the incidence of shoulder disorders (Larsson, Søgaard, and Rosendal 2007; Pope et al. 1997; Bernard and Putz-Anderson 1997). Shoulder postural changes were estimated from the videos when the upper arm and torso angle increased and when the arm was flexed, extended, abducted, adducted, and/or externally/internally rotated. Moreover, unsupported upper arm postures for cases of sustained or repeated postures with loads were also included in the analysis. The analysis involved axial rotation/lateral bending of the torsos, torso angle and head angle. The sampling rate for the videos was 60 Hz and the observational analysis was completed at half the sampling rate. Angles were estimated from the videos for the most awkward posture. To ensure that postural estimates were as accurate as possible, the digital human in the University of Michigan's model (3DSSPP version 6.0.6) was used to simulate the task being analysed. Figure 2 shows an example of a task done and its corresponding simulated task in 3DSSPP.

The 3DSSPP model was also used to estimate the shoulder moments at each shoulder joint required for DPC estimation. Both the postural estimates and the loads carried were used for moment calculations. Loads carried and their magnitudes were retrieved from the epidemiological dataset.

To obtain the number of cycles to failure, the ultimate strength of the shoulders needs to be estimated. Both the shoulder moments at each shoulder joint and the shoulder strength capability were used to estimate the ultimate strength for the shoulder. The

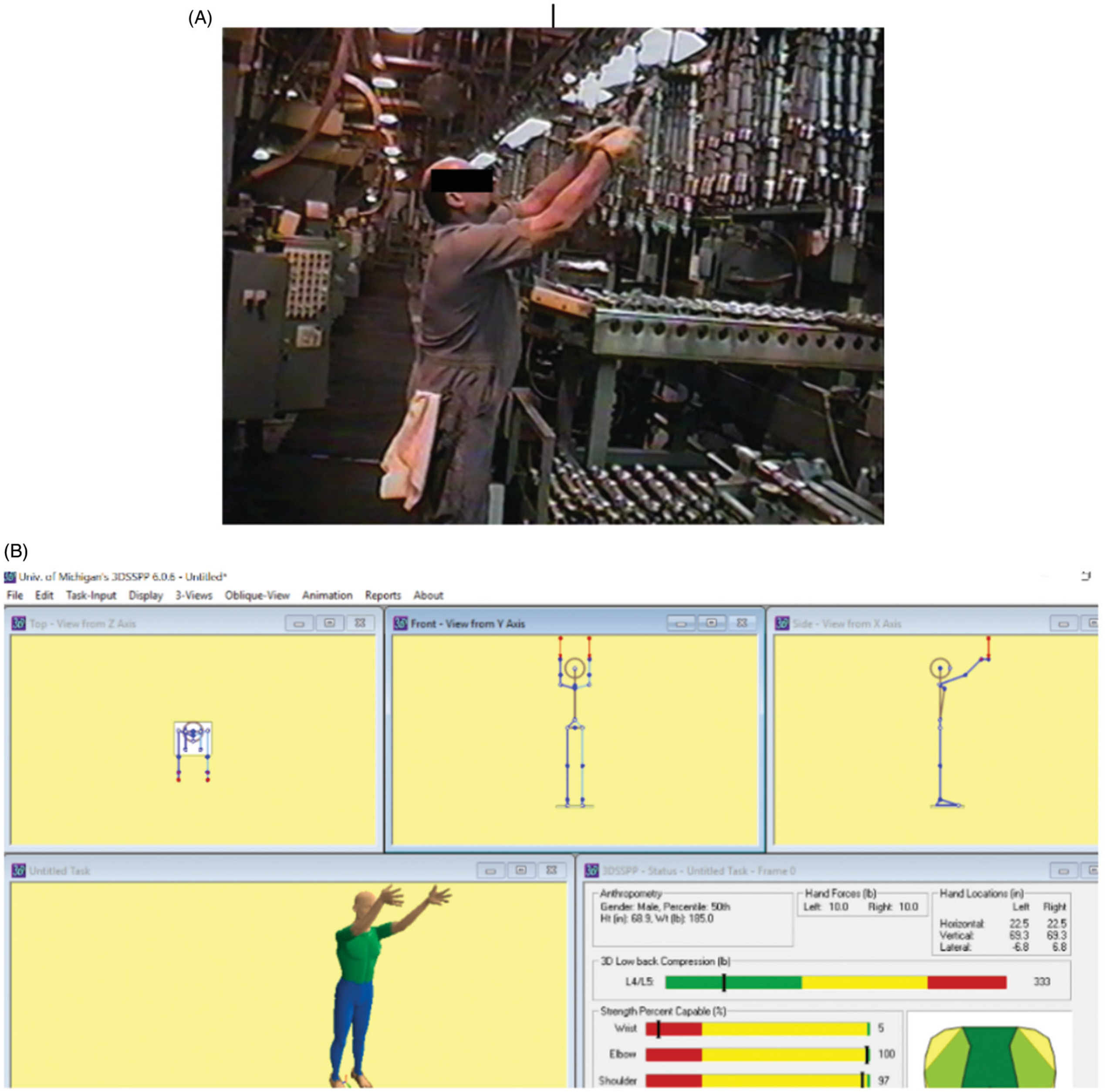


Figure 2. (A) An example of shoulder task and (B) its corresponding digital 3 D human simulation (University of Michigan 3DSSPP, © 2017 The Regents of the University of Michigan).

shoulder strength capability estimates were obtained from 3DSSPP (50% male population, lifting standing, average for left and right shoulders). Equation (1) was then used to get the number of cycles to failure for left and right shoulders from which the reciprocal was equal to the DPC. Equation (2) was then used to calculate the job CD for the left and right shoulder separately. The job CD was estimated by summing the multiplication of the DPC for each task by the corresponding number of repetitions completed per workday. An assumption was also made that the higher CD value between the shoulders (left or right) would be responsible for a higher probability of a shoulder outcome. Table 1 demonstrates an example for the daily dose CD calculations for a job (Job A) involving two tasks.

2.3. Validation of the tool

The epidemiology database included symptoms from a structured interview and historical records for injury data, for all jobs analysed. Health outcomes used in the validation included pain today, pain last year, records for injury data for neck and shoulder and

Table 1. Example of a daily dose cumulative damage (CD) calculations for a two tasks job.

Tasks for job A	DPC RS	DPC LS	Reps/min	CD RS	CD LS	JOB CD RS	JOB CD LS	CD MAX	CD/day
1	1.496E-06	5.108E-07	2.50	3.740E-06	1.277E-06	5.403E-05	2.651E-06	5.403E-05	0.025933
2	2.011E-05	5.497E-07	2.50	5.029E-05	1.374E-06				

DPC RS: damage per cycle for right shoulder; DPC LS: damage per cycle for left shoulder; CD RS: CD for right shoulder; CD LS: CD for left shoulder.

subject outcome attribution of the current job's relationship to injury or pain. FTOVs were reported at the job level; whereas, pain and attribution reports were reported at the subject level. A visual analog scale (VAS) was used to rate pain in different body parts including the shoulder. Discomfort and injury symptoms were self-reported on the day of the interview, and retrospectively for the past year. Subject outcome attribution of job relationship was also reported by the workers and classified into five categories: Category 1: Symptoms resulting from current job (Job-related); Category 2: aggravated by current job, but not resulting from current job (Job-aggravated); Category 3: Symptoms did not change and did not result from current job; Category 4: Symptoms did not result from current job and improved; Category 5: No symptoms present.

A daily dose of CD was obtained by summing the CD associated with the different tasks comprising a job. The highest value of CD for the left and right shoulders was used in the analysis under the assumption that the highest value is associated with a higher probability of a shoulder MSD. Different definitions of cases and controls were used in the validation, for example current shoulder pain (categories 1,2) versus current shoulder pain (categories 4,5). This would compare those with current shoulder pain judged to have originated on, or was aggravated by, the current job (a positive case) versus those reporting either symptom improvement of a lack of symptoms due to the current job (a negative case). Similarly, the contrast of current shoulder pain (category 1 vs. category 5) would compare those with shoulder pain originating on the job versus those reporting no symptoms due to the job. Similar outcomes were also considered for shoulder pain last year as well as job-level FTOV injury record. To be considered a case, the VAS score had to exceed 15 mm (VAS ranged from 0 to 100 mm with 0 = no pain at all and 100 = worst pain imaginable), consistent with previously published studies (Gallagher et al. 2017, 2018).

Both crude and adjusted binary logistic regressions were used in the analysis to test the model significance. The analysis considered multiple workers performing the same job. Sex, age, plant site and body mass index (BMI) were included as covariates for the adjusted binary logistic regression model. Sex, age and BMI were dichotomised. Values of 1 were used for male subjects, those greater than 40 years of age, and those with a BMI greater than 30. Regression equations were used to determine the relationship between the log of CD measure and the probability of an outcome (positive case) using the following equation:

$$P(\text{event}) = \exp(Y')/(1 + \exp(Y')) \tag{3}$$

where Y' relationship will be derived from the logistic regression equation:

$$Y' = \beta 0 + \beta 1 \times \text{Log CD} \tag{4}$$

Thus, this regression equation can be used to estimate the probability of a shoulder outcome for each value of CD.

3. Results

Overall outcomes and the sample demographic characteristics are summarised in Table 2.

A summary of crude and adjusted logistic regression results for all five outcomes is provided in Table 3. A significant relationship was found between the Log CD measure and all shoulder outcomes in both crude and adjusted models. For the FTOV outcome, if any of the workers reported an injury it was considered a case, therefore, only plant site was included in the analysis as a covariate. Plant site demonstrated a significant relationship ($\chi^2_5 = 13.04$, $p = 0.023$). The odds ratio for the Log CD measure when the injury record data for shoulder FTOV were used was 2.59 (95% CI: 1.73, 3.89).

For the shoulder pain today outcome, the model remained significant ($\chi^2_9 = 34.31$, $p < 0.001$), and the Log CD odds ratio was 2.12 with a 95% CI of (1.37, 3.28). Sex demonstrated a significant relationship ($\chi^2_1 = 8.64$, $p = 0.003$) for the Pain Today outcome. When shoulder pain last year was used as the outcome, the logistic regression was significant ($\chi^2_9 = 45.90$, $p < 0.001$), and the Log CD odds ratio

Table 2. Demographic and outcome characteristics for the study subjects.

Outcomes	All study subjects	Cases	Non-cases
Injury (first time office visit for shoulder symptoms) FTOV			
Total *N*	293	76	217
Age group, *n* (%)			
<=40	155 (52.9)	46 (60.5)	109 (50.2)
>40	138 (47.1)	30 (39.5)	108 (49.8)
Sex, *n* (%)			
Female	81 (27.6)	23 (30.3)	58 (26.7)
Male	212 (72.4)	53 (69.7)	159 (73.3)
BMI, *n* (%)			
<30	231 (78.8)	63 (82.9)	168 (77.4)
>=30	62 (21.2)	13 (17.1)	49 (22.6)
Pain today			
Total *N*	293	47	246
Age group, *n* (%)			
<=40	155 (52.9)	30 (63.8)	125 (50.8)
>40	138 (47.1)	17 (36.2)	121 (49.2)
Sex, *n* (%)			
Female	81 (27.6)	22 (46.8)	59 (24)
Male	212 (72.4)	25 (53.2)	187 (76)
BMI, *n* (%)			
<30	231 (78.8)	39 (83)	192 (78)
>=30	62 (21.2)	8 (17)	54 (22)
Pain last year			
Total *N*	293	74	219
Age group, *n* (%)			
<=40	155 (52.9)	39 (52.7)	116 (53)
>40	138 (47.1)	35 (47.3)	103 (47)
Sex, *n* (%)			
Female	81 (27.6)	30 (40.5)	51 (23.3)
Male	212 (72.4)	44 (59.5)	168 (76.7)
BMI, *n* (%)			
<30	231 (78.8)	58 (78.4)	173 (79)
>=30	62 (21.2)	16 (21.6)	46 (21)
Self-reported symptoms (1,2 vs 4,5)			
Total *N*	282	51	231
Age group, *n* (%)			
<=40	149 (52.8)	27 (52.9)	122 (52.8)
>40	133 (47.2)	24 (47.1)	109 (47.2)
Sex, *n* (%)			
Female	74 (26.2)	19 (37.3)	55 (23.8)
Male	208 (73.8)	32 (62.7)	176 (76.2)
BMI, *n* (%)			
<30	222 (78.7)	40 (78.4)	182 (78.8)
>=30	60 (21.3)	11 (21.6)	49 (21.2)
Self-reported symptoms (1 vs 5)			
Total N	261	41	220
Age group, *n* (%)			
<=40	136 (52.1)	21 (51.2)	115 (52.3)
>40	125 (47.9)	20 (48.8)	105 (47.7)
Sex, *n* (%)			
Female	66 (25.3)	14 (34.1)	52 (23.6)
Male	195 (74.7)	27 (65.9)	168 (76.4)
BMI, *n* (%)			
<30	204 (78.2)	30 (73.2)	174 (79.1)
>=30	57 (21.8)	11 (26.8)	46 (20.9)

was 2.85 with a 95% CI of (1.88, 4.32). Sex demonstrated a significant relationship ($\chi^2_1 = 7.55,\ p = 0.006$).

The logistic regression results for current shoulder pain using job outcome attribution (1,2 vs 4,5) showed significant results with log CD and when adjusting for covariates ($\chi^2_9 =\ 63.89,\ p < 0.001$). Log CD was significant ($\chi^2_1 = 49.51,\ p < 0.001$); however, none of the other covariates demonstrated a significant relationship. Age and sex, however, did show a trend towards significance with probabilities <0.10. The odds ratio for current shoulder pain (with job attribution) was 5.20 with a 95% CI of (3.02, 8.95). Finally, the logistic regression results for current shoulder pain with job outcome attribution (1 vs. 5) showed significant results with Log CD adjusting for covariates ($\chi^2_9 = 46.17,\ p < 0.001$). Log CD was significant ($\chi^2_1 = 29.15,\ p < 0.001$), and none of the covariates showed a significant relationship. However, age did show a trend towards a significance level of 0.10. The Odds ratio was 3.98 with a 95% CI of (2.28, 6.94).

Table 3. Summary of the crude and adjusted ORs for the different shoulder outcomes.

Outcome	Analysis	Cases	*N*	Variable	*df*	x^2	*p*	OR	95% CI
Pain today	Crude	46	293	**Log CD**	**1**	**16.11**	**<0.001**	**2.23**	**(1.49, 3.32)**
	Adjusted	46	293	**Log CD**	**1**	**11.88**	**0.001**	**2.12**	**(1.37, 3.28)**
				Age	1	0.09	0.767	0.89	(0.41, 1.95)
				Sex	**1**	**8.64**	**0.003**	**0.34**	**(0.17, 0.69)**
				BMI	1	0.37	0.541	0.76	(0.31, 1.85)
				Site	5	6.08	0.299	Var	Var
Pain last year	Crude	74	293	**Log CD**	**1**	**32.35**	**<0.001**	**2.83**	**(1.91, 4.19)**
	Adjusted	74	293	**Log CD**	**1**	**28.78**	**<0.001**	**2.85**	**(1.88, 4.32)**
				Age	1	0.99	0.319	1.40	(0.72, 2.73)
				Sex	**1**	**7.55**	**0.006**	**0.42**	**(0.22, 0.78)**
				BMI	1	0.01	0.917	1.04	(0.51, 2.14)
				Site	5	3.79	0.581	Var	Var
FTOV	Crude	76	293	**Log CD**	**1**	**26.95**	**<0.001**	**2.53**	**(1.74, 3.69)**
	Adjusted	76	293	**Log CD**	**1**	**24.61**	**<0.001**	**2.59**	**(1.73, 3.89)**
				Site	**5**	**13.04**	**0.023**	**Var**	**Var**
1,2 vs. 4,5	Crude	51	282	**Log CD**	**1**	**52.41**	**<0.001**	**4.73**	**(2.88, 7.79)**
	Adjusted	51	282	**Log CD**	**1**	**49.51**	**<0.001**	**5.20**	**(3.02, 8.95)**
				Age	1	3.45	0.063	2.14	(0.95, 4.79)
				Sex	1	3.63	0.057	0.47	(0.22, 1.01)
				BMI	1	0.01	0.909	1.05	(0.44, 2.52)
				Site	**5**	**5.15**	**0.398**	**Var**	**Var**
1 vs. 5	Crude	41	261	**Log CD**	**1**	**34.24**	**<0.001**	**3.88**	**(3.32, 6.48)**
	Adjusted	41	261	**Log CD**	**1**	**29.15**	**<0.001**	**3.98**	**(2.28, 6.94)**
				Age	1	3.68	0.055	2.29	(0.98, 5.36)
				Sex	1	1.59	0.208	0.59	(0.26, 1.33)
				BMI	1	0.92	0.338	1.56	(0.64, 3.83)
				Site	**5**	7.86	0.164	Var	Var

Note: N: total number; Var: various, *df*: degrees of freedom; FTOV: first time office visit, see text for definitions of Outcome 1,2 vs. 4,5 and Outcome 1 vs. 5. Bold values represent statistically significant results.

Figure 3 shows the binary fitted line plots for the different shoulder outcomes. Higher values of log CD were associated with an increase in the probability of a shoulder outcome. Some of the plots also indicate a few extreme points (referencing jobs with high force requirements for lifting and pushing tasks) with high values of log CD. It should be noted that the predictive range for the probability of a shoulder outcome to occur decreased when using the shoulder pain today measure in the analysis. The few cases reported for shoulder pain today, even for highly demanding jobs, might explain this result.

4. The Shoulder Tool

The relationships demonstrated between the Log CD measure and the shoulder outcomes observed in the epidemiological database considered provide further support of fatigue failure theory as an aetiological mechanism for the development of work-related MSDs (Gallagher and Schall 2017). A new ergonomic risk assessment tool for the shoulder based on material fatigue failure theory, The Shoulder Tool, which provides a CD measure for the shoulder representing cumulative loading on the shoulders during a workday was thus developed for use by ergonomics practitioners and researchers. The tool is designed to be easy to use requiring simple inputs from users. Four pieces of information are necessary for The Shoulder Tool which include: type of task being performed, the hand load, distance from the acromion to centre of the load (greatest distance), and repetitions in a workday for the analysed tasks. The distance from the acromion to the load or hand can be horizontal, vertical or straight from the acromion to centre of load depending on the type of task analysed (i.e. lifting, pushing, pulling) (Figures 4–7). A measuring tape can be used to measure the distance from the acromion to the centre of the load or hand. The tool provides analysis for each shoulder separately, thus the greatest lever arm for one shoulder does not need to happen at the same time as the other one. The Shoulder Tool provides the probability of a clinic visit for a shoulder MSD associated with a particular job, based on the relationship shown above.

4.1. Assessing mono-task jobs

A shoulder intensive monotask job, involving a task done repetitively throughout a workday, can be easily analysed using The Shoulder Tool. An example is a task where a 9 N load is handled using the right shoulder and the lever arm is 41 cm. The repetitions per workday is 2880. Figure 8 shows a screenshot of The Shoulder Tool for this task. The probability of a right shoulder outcome is relatively low at 20.8%.

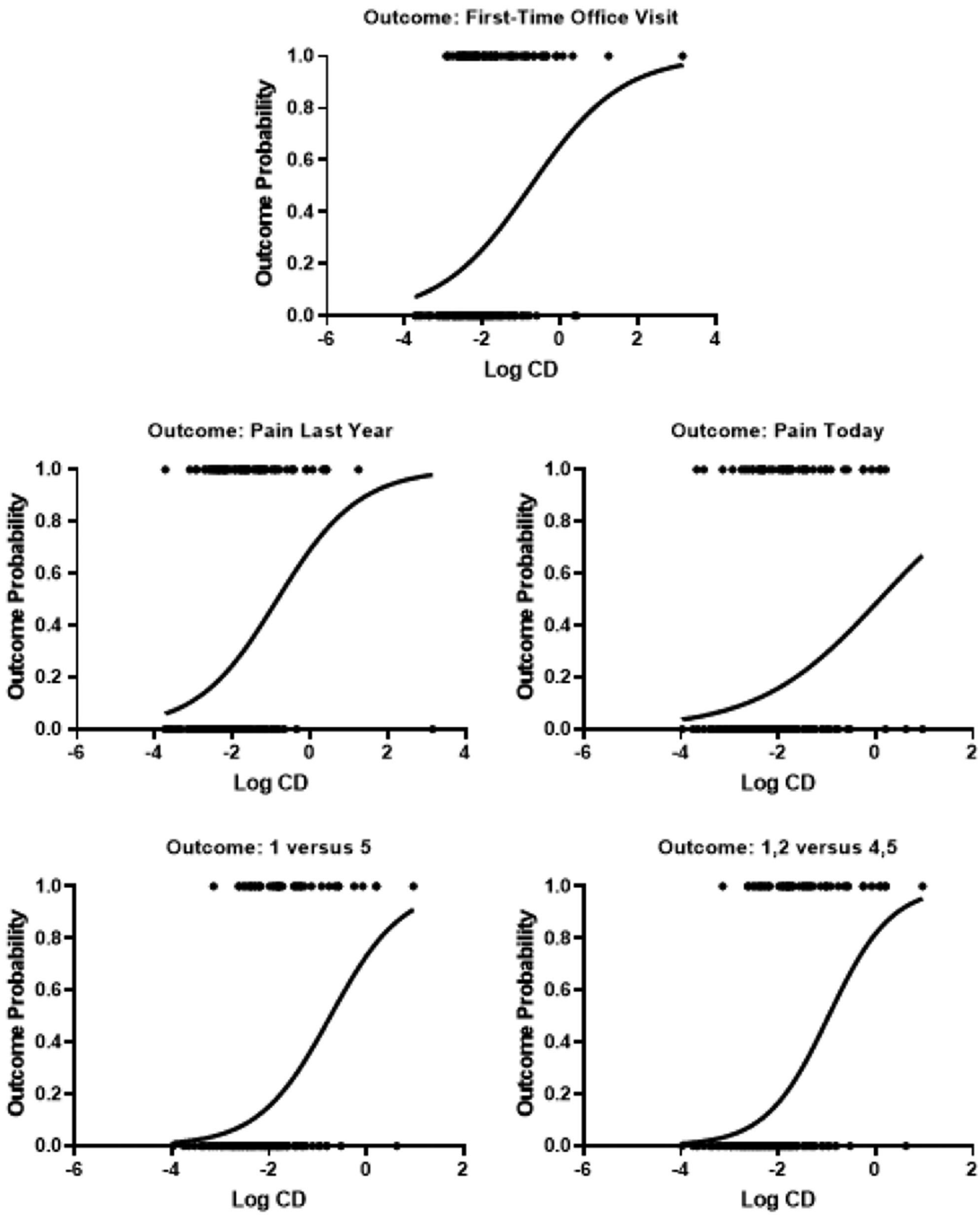


Figure 3. Relationship of outcome probabilities to the Log CD measure of The Shoulder Tool for five shoulder outcomes (see text for outcome definitions).

Another example of a monotask where both hands are used, is a 45 N panel lifted from a conveyor to a rack. In this example, the weight can be evenly distributed between the hands (22.5 N in each). The repetition of the task is 4800 times per shift. The lever arm is 46 cm. The risk associated with this task will be the same for each shoulder because of the even distribution of the load and the identical lever arms. A screenshot of the analysis is shown below, Figure 9.

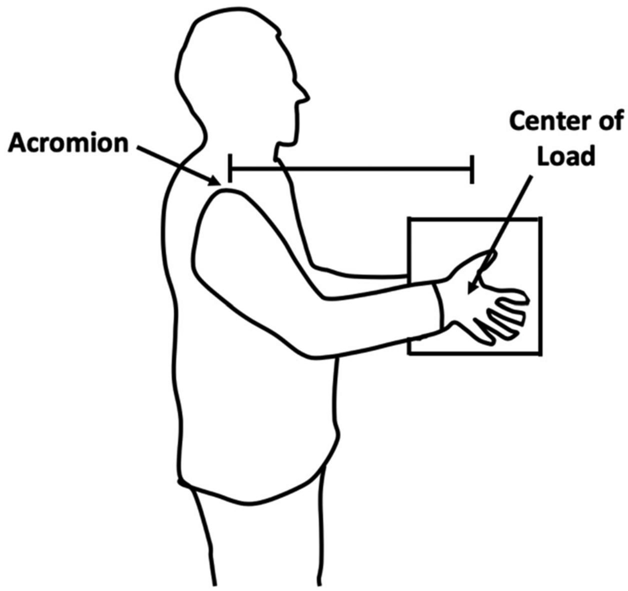


Figure 4. An illustration of the horizontal lever arm measurement for sagittal load handling. Measurement is taken from the acromion to the centre of the load at the load's maximum horizontal distance from the shoulder during the handling task.

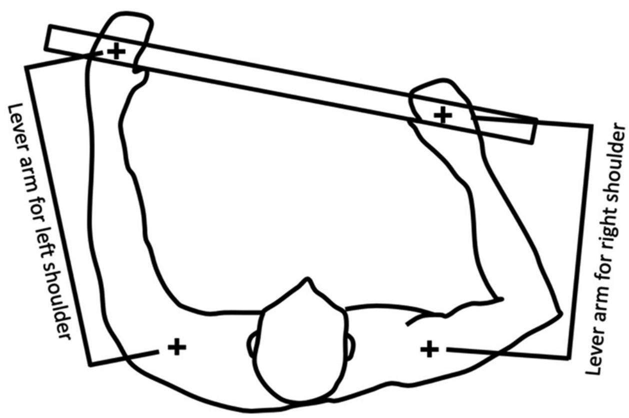


Figure 5. A manual handling task and measurements of the lever arms for both left and right shoulders. The weight of the object being handled may be divided between the hands done evenly or unevenly (i.e. one shoulder is bearing more weight) which can be estimated by the analyst.

4.2. Assessing jobs with multiple shoulder tasks

For jobs with variable tasks and various exertions, The Shoulder Tool provides a daily dose CD for each shoulder by summing the CD for each task. Moreover, the tool provides the percentage contribution for the total CD associated with each task. An example is provided in Figure 10. In this example, task 3 is associated with the highest percentage of CD, thus a priority should be given to task 3 in terms of ergonomic intervention strategies.

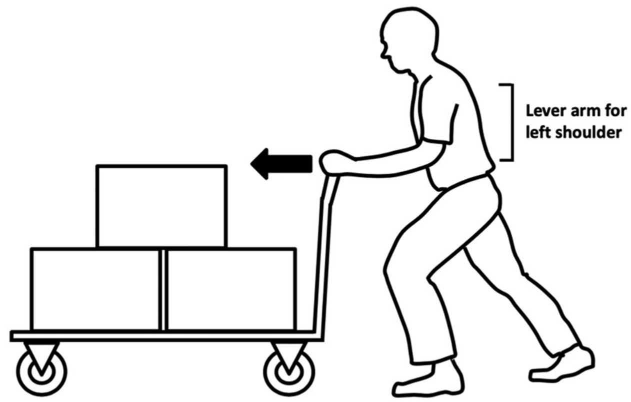


Figure 6. Vertical measurement for the lever arm for forward pushing/pulling backward tasks. Force gauges may be used to estimate the forces. Peak forces should be estimated such as the forces required to get the cart to move.

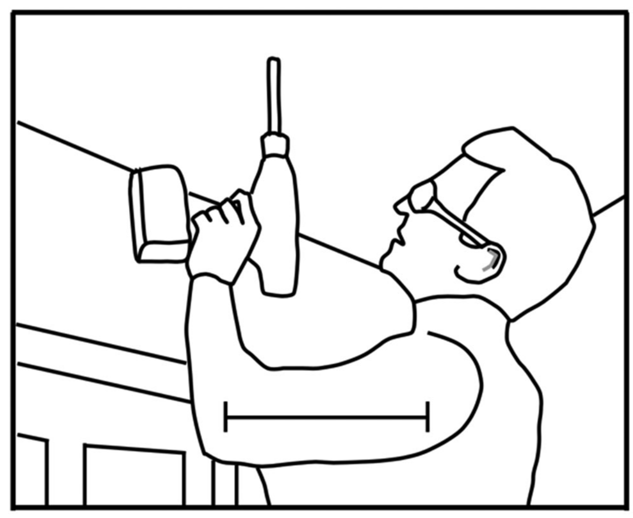
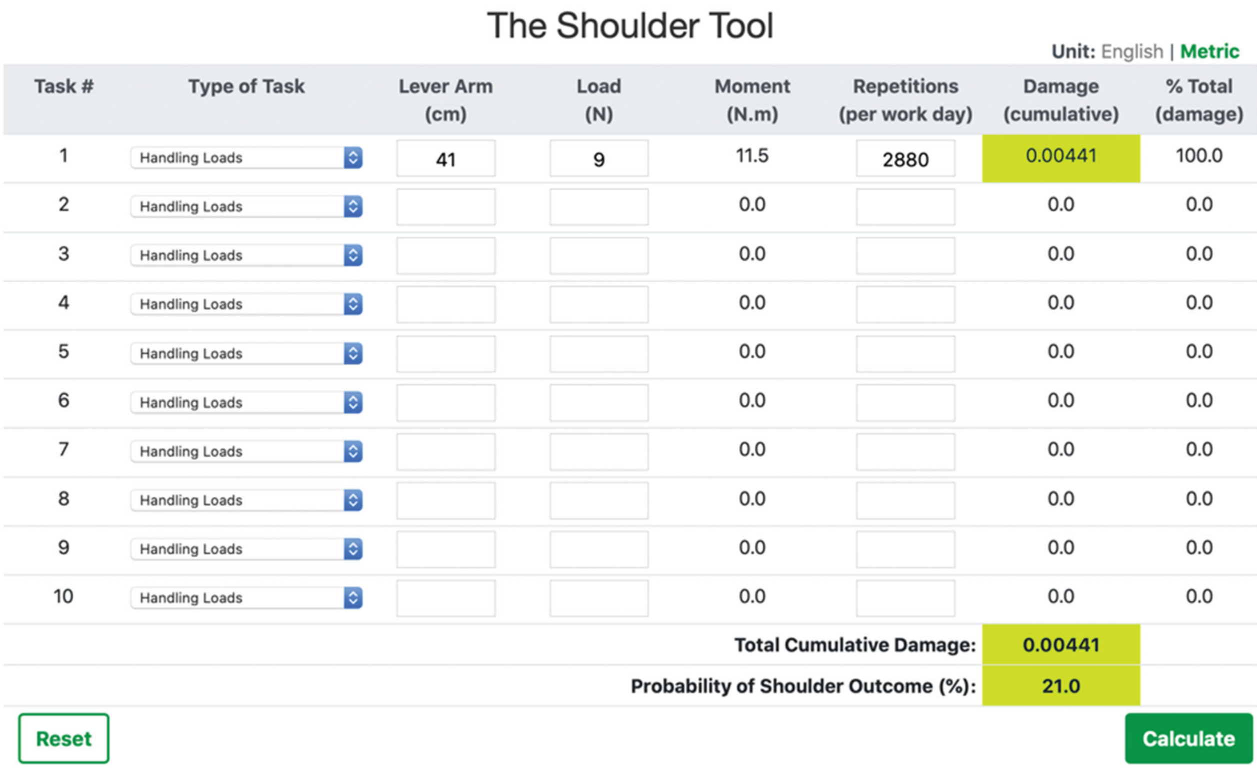


Figure 7. Lever arm measurement for an upward push task. A pulling down action for the same posture may be also analysed using the same lever arm measurement.

4.3. Assessing highly variable shoulder jobs

For jobs with highly variable shoulder intensive tasks, a binning procedure can be used. An example of the use of the Shoulder Tool using a binning procedure is a warehouse picker completing lifts of different items. Table 4 demonstrates an example of a warehouse picking task using the right shoulder to lift many items.

For this analysis, tasks can be grouped into bins based on their peak moments and the repetitions for the tasks in the same bin can be summed to arrive at the repetitions for each bin. In this example, three bins will be used for the analysis, bin 1 (1–15 Nm), bin 2 (16–30 Nm), and bin 3 (31–45 Nm). The tasks will be then grouped into their corresponding bin and the repetitions will be summed for the tasks within each bin.



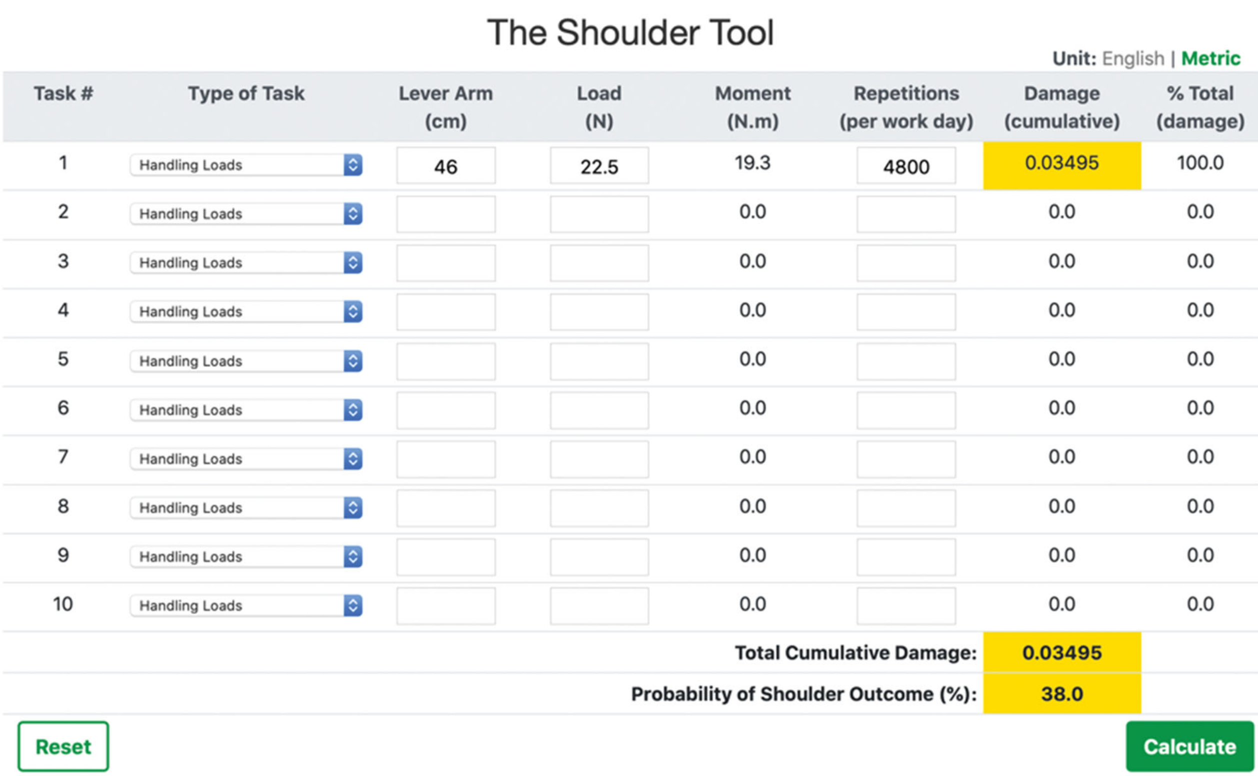
The Shoulder Tool

Unit: English | Metric

Task #	Type of Task	Lever Arm (cm)	Load (N)	Moment (N.m)	Repetitions (per work day)	Damage (cumulative)	% Total (damage)
1	Handling Loads	41	9	11.5	2880	0.00441	100.0
2	Handling Loads			0.0		0.0	0.0
3	Handling Loads			0.0		0.0	0.0
4	Handling Loads			0.0		0.0	0.0
5	Handling Loads			0.0		0.0	0.0
6	Handling Loads			0.0		0.0	0.0
7	Handling Loads			0.0		0.0	0.0
8	Handling Loads			0.0		0.0	0.0
9	Handling Loads			0.0		0.0	0.0
10	Handling Loads			0.0		0.0	0.0
					Total Cumulative Damage:	0.00441	
					Probability of Shoulder Outcome (%):	21.0	

Reset | Calculate

Figure 8. The Shoulder Tool results for the analysis of a monotask job.



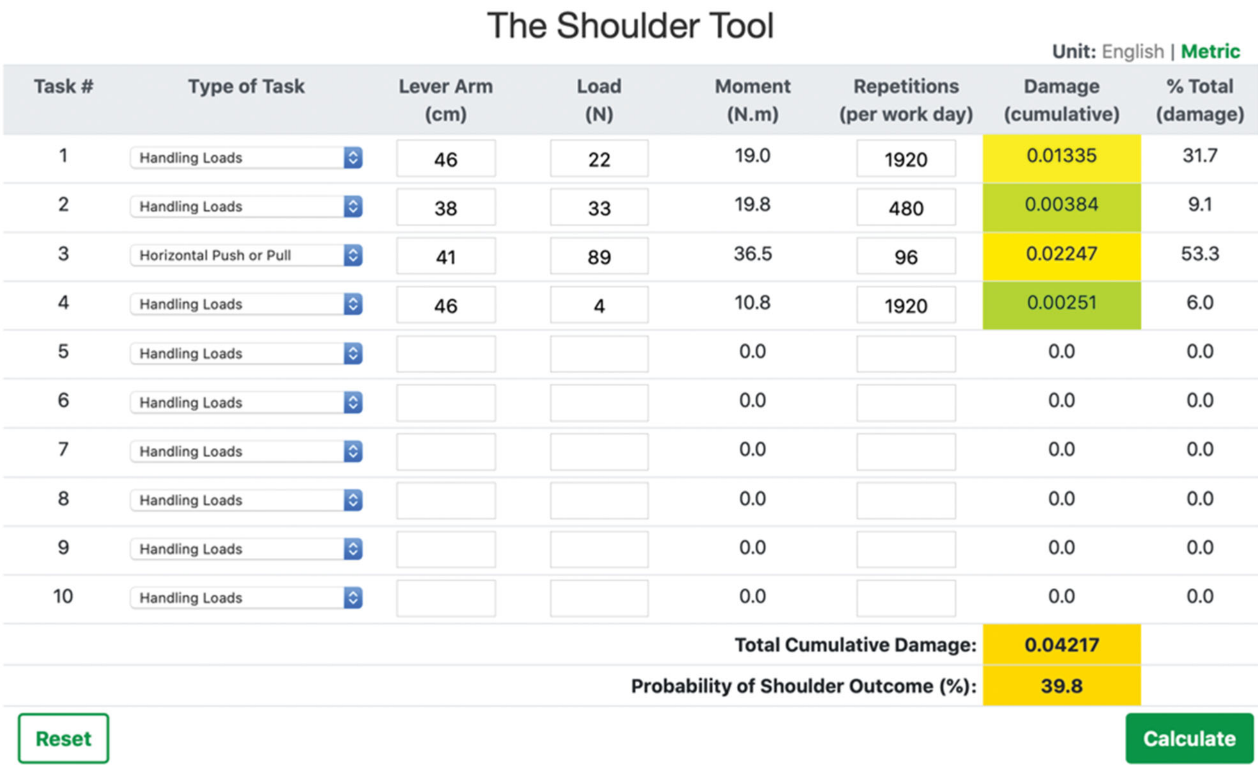
The Shoulder Tool

Unit: English | Metric

Task #	Type of Task	Lever Arm (cm)	Load (N)	Moment (N.m)	Repetitions (per work day)	Damage (cumulative)	% Total (damage)
1	Handling Loads	46	22.5	19.3	4800	0.03495	100.0
2	Handling Loads			0.0		0.0	0.0
3	Handling Loads			0.0		0.0	0.0
4	Handling Loads			0.0		0.0	0.0
5	Handling Loads			0.0		0.0	0.0
6	Handling Loads			0.0		0.0	0.0
7	Handling Loads			0.0		0.0	0.0
8	Handling Loads			0.0		0.0	0.0
9	Handling Loads			0.0		0.0	0.0
10	Handling Loads			0.0		0.0	0.0
					Total Cumulative Damage:	0.03495	
					Probability of Shoulder Outcome (%):	38.0	

Reset | Calculate

Figure 9. A screenshot of a monotask two-handed lift of a 45 N load assuming even weight distribution on each shoulder.



The Shoulder Tool

Unit: English | Metric

Task #	Type of Task	Lever Arm (cm)	Load (N)	Moment (N.m)	Repetitions (per work day)	Damage (cumulative)	% Total (damage)
1	Handling Loads	46	22	19.0	1920	0.01335	31.7
2	Handling Loads	38	33	19.8	480	0.00384	9.1
3	Horizontal Push or Pull	41	89	36.5	96	0.02247	53.3
4	Handling Loads	46	4	10.8	1920	0.00251	6.0
5	Handling Loads			0.0		0.0	0.0
6	Handling Loads			0.0		0.0	0.0
7	Handling Loads			0.0		0.0	0.0
8	Handling Loads			0.0		0.0	0.0
9	Handling Loads			0.0		0.0	0.0
10	Handling Loads			0.0		0.0	0.0
					Total Cumulative Damage:	0.04217	
					Probability of Shoulder Outcome (%):	39.8	

Reset Calculate

Figure 10. A multitask job analysed using The Shoulder Tool.

Table 4. An example for the use of the binning procedure in The Shoulder Tool.

Item	Lever arm(cm)	Load (N)	Moment (Nm)	Repetitions
1	31	36	16.9	10
2	46	62	37.4	22
3	51	67	44.2	39
4	41	45	26.3	13
5	38	18	14.1	27
6	41	36	22.6	11
7	36	12	11.1	22
8	40	42	24.4	26
9	30	15	10.0	20
…	…	…	…	…

Note: Moment includes a moment due to the weight of the forearm and hand based on lever arm.

For example, tasks 5, 7, and 9 would be among those grouped into bin 1 and their corresponding repetition within that bin totals 157. This bin will represent the first task in the shoulder tool with 157 repetitions. The binning analysis for the other two bins will be completed in a similar way. Thus, the second bin (16–30 Nm) includes tasks 1, 4, 6, and 8 among others and has 122 repetitions. The third bin (31–45 Nm) includes tasks 2 and 3 among others and has 105 repetitions. While this binning procedure is easy to use, gives reasonably close results, and simplifies the analysis, some inflation in the probability may result. Thus, using the narrowest range possible for binning is recommended. Figure 11 shows a screenshot of the results.

5. Discussion

This study revealed a strong association between the Log CD measure generated by The Shoulder Tool and multiple shoulder MSD outcomes, providing evidence that fatigue failure may be an important aetiological factor in the development of shoulder MSDs. The dose-response associations were observed for the pain prevalence, self-reported symptoms, and FTOV outcomes. From the binary fitted line plots, a dose-response relationship can be observed between the Log CD score and the probability of all five shoulder outcomes. Some of the binary fitted line plots also have a few extreme points (representing jobs with high force requirements for lifting and pushing tasks) with high values of log CD. This may be explained by differences among workers in reporting a shoulder outcome and their interpretation of shoulder pain. It should be noted that the predictive range for the probability of a shoulder outcome decreased when using the shoulder pain today outcome in the analysis. The decrease in cases reported for shoulder pain today even for highly demanding jobs could explain this result and the predictive range.

Self-reported symptoms involving job outcome attribution demonstrated higher ORs compared to other shoulder outcomes. Most of the workers reported 1 or 5 for that outcome, and those values were used to define a case or non-case in the analysis.

The Shoulder Tool

Unit: English | **Metric**

Task #	Type of Task	Lever Arm (cm)	Load (N)	Moment (N.m)	Repetitions (per work day)	Damage (cumulative)	% Total (damage)
1	Handling Loads	31	30	15.0	157	0.00048	0.3
2	Handling Loads	31	78.3	30.0	122	0.00770	5.3
3	Handling Loads	31	126.8	45.0	105	0.13746	94.4
4	Handling Loads			0.0		0.0	0.0
5	Handling Loads			0.0		0.0	0.0
6	Handling Loads			0.0		0.0	0.0
7	Handling Loads			0.0		0.0	0.0
8	Handling Loads			0.0		0.0	0.0
9	Handling Loads			0.0		0.0	0.0
10	Handling Loads			0.0		0.0	0.0
					Total Cumulative Damage:	**0.14564**	
					Probability of Shoulder Outcome (%):	**52.2**	

Reset | Calculate

Figure 11. An application of the use of the binning procedure for a highly variable shoulder intensive tasks. Note that The Shoulder Tool adds a moment due to the forearm and hand weight based on lever arm.

For the covariates included in the analysis, sex and site demonstrated significant relationships for some of the shoulder outcomes. However, none of the other covariates demonstrated significant relationships.

The strong associations between the CD measure and all shoulder outcomes supports our fatigue failure model with respect to the aetiology of MSDs. As mentioned previously, in vitro testing, epidemiological studies, and loading of tissues in animal studies all support the evidence behind the fatigue failure process and MSD development. Many biological tissues have been tested in in-vitro studies which include tendons (Schechtman and Bader 1997; Wang, Ker, and Alexander 1995); cartilage (Bellucci and Seedhom 2001); ligaments (Thornton, Schwab, and Oxland 2007; Lipps, Wojtys, and Ashton-Miller 2013) and spinal motion segments (Brinckmann, Biggemann, and Hilweg 1988; Gallagher et al. 2005).

Recently, material fatigue theory has been used by Gallagher et al. (2017, 2018) to develop two new risk assessment tools, one for the distal upper extremity (the Distal Upper Extremity Tool, or DUET) and one for the low back, the Lifting Fatigue Failure Tool (LiFFT). In DUET, the authors estimated the force exertion using the OMNI-RES scale along with respective repetitions per workday to get estimates of CD in a similar manner as the suggested methodology in the current study (Gallagher et al. 2018). In LiFFT, estimates of DPC were obtained by estimating compressive load based on peak load moment for a lift. The latter tool used data from fatigue failure studies for the spinal motion segments (Gallagher et al. 2017). Both LiFFT and DUET were validated using the same epidemiological study database used here. The current results indicate that the application of the fatigue failure method also works well in assessing the probability of association with shoulder outcomes. The Shoulder Tool can be used for both comparative redesign purposes and as a screening tool. A comprehensive risk assessment can be implemented for workers using the three tools to assess the risk to the low back, upper extremities, and the shoulder.

As can be seen in Figures 8, 10, and 11, The Shoulder Tool provides a total cumulative damage score and an associated probability of a shoulder outcome. The authors have used a "heat map" to provide some guidance regarding the shoulder risk associated with a job, based on the probability of an outcome. We have resisted the urge to set specific cut points for risk because it is a continuous relationship, and there is no specific point at which the risk suddenly "jumps" to a new level. However, we believe jobs with an outcome probability of 25% or less (green jobs) would generally be considered safe for the majority of workers, and jobs with a 50% probability or greater (red jobs) would be unacceptable for most workers and job resign would be recommended in these cases. In between these two extremes (the yellow green to orange jobs) would be jobs that deserve careful analysis and may require job redesign. Obviously, the closer to red the analysis result is, the higher the job risk. Lower probabilities should always be safer.

The Shoulder Tool overcomes the limitations of other observational exposure assessment tools commonly used to evaluate shoulder intensive work tasks. In particular, RULA and REBA do not allow for examining the effect of cumulative loading and they do not consider a variety of risk factors (McAtamney and Corlett 1993; Hignett and McAtamney 2000; Janowitz et al. 2006; Takala et al. 2010). Another shortcoming is the inability to provide the probability of an injury risk. Inability to deal with multitask jobs is another shortcoming of previous tools, as many jobs are multitask in nature (Padula et al. 2017).

Some limitations of the current version of The Shoulder Tool are that it does not account for all loading conditions such as when an arm is held straight in line with the shoulder such as a push forward action when stress in the shoulder will be generated even though no moment is present. Another example is when the arm is held straight above the shoulder. Although a low moment is created, intensive muscle contraction is taking place and this loading condition can contribute to physiological (and material) fatigue. Study limitations include the fact that only the most difficult postures were included in the analysis and other risk factors such as the personal characteristics, speed of work and duty/rest cycles were not considered. The effect of personal characteristics for adjusting the moment calculations was not included. An assumption has been also made that the higher value of CD between the shoulders is responsible for a higher probability of a shoulder outcome. Also, the tool does not account for the additional load associated with continuous overhead work. Rest intervals were not factored into our model given unknowns regarding the role of rest in healing. To estimate the CD, data collection is needed to obtain a complete job description, this requires time and effort and we are investigating ways to partially automate the process in the future. The associations found between the CD measure and the different shoulder outcomes provided further support for the role of fatigue failure as an aetiological factor in the development of shoulder MSDs. Further research is necessary to quantify the postural estimates and account for the dynamic biomechanical nature of the jobs analysed.

6. Conclusion

Based on the results of this study, the following conclusions may be drawn:

- The Shoulder Tool demonstrated dose-response relationships for all five shoulder outcomes studied. Odds ratios for the tool's continuous Log CD measure ranged from 2.12 to 5.19 in analyses adjusted for age, sex, BMI, and plant site.
- As with previous fatigue failure-based risk assessment tools (LiFFT and DUET) developed by the authors, The Shoulder Tool demonstrated strong associations with outcomes, suggesting that fatigue failure may be an aetiologically significant factor for a wide range of MSDs.
- A web-based version of The Shoulder Tool and a user manual are freely accessible at https://the-shouldertool.pythonanywhere.com.
- A downloadable Microsoft Excel version is available (which allows saving of analyses) is available at http://eng.auburn.edu/occupational-safety-ergonomics-injury-prevention/research/research%202.html.

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

Pribicevic, M. 2012. "The Epidemiology of Shoulder Pain: A Narrative Review of the Literature." In *Pain in Perspective*, edited by S. Ghosh. Rijeka: IntechOpen.

Wang, X. T., R. F. Ker, and R. M. Alexander. 1995. "Fatigue Rupture of Wallaby Tail Tendons." *The Journal of Experimental Biology* 198 (Pt 3): 847–852.

Andersen, J. H., A. Kaergaard, S. Mikkelsen, U. F. Jensen, P. Frost, J. P. Bonde, and J. F. Thomsen. 2003. "Risk Factors in the Onset of Neck/Shoulder Pain in a Prospective Study of Workers in Industrial and Service Companies." *Occupational and Environmental Medicine* 60 (9): 649–654. doi:10.1136/oem.60.9.649.

Andersen, Johan Hviid, Anette Kaergaard, Poul Frost, Jane Frølund Thomsen, Jens Peter Bonde, Nils Fallentin, Vilhelm Borg, and Sigurd Mikkelsen. 2002. "Physical, Psychosocial, and Individual Risk Factors for Neck/Shoulder Pain with Pressure Tenderness in the Muscles among Workers Performing Monotonous, Repetitive Work." *Spine* 27 (6): 660–667. doi:10.1097/00007632-200203150-00017.

Barbe, M. F., S. Gallagher, V. S. Massicotte, M. Tytell, S. N. Popoff, and A. E. Barr-Gillespie. 2013. "The Interaction of Force and Repetition on Musculoskeletal and Neural Tissue Responses and Sensorimotor Behavior in a Rat Model of Work-Related Musculoskeletal Disorders." *BMC Musculoskeletal Disorders* 14 (1): 303. doi:10.1186/1471-2474-14-303.

Bellucci, G., and B. B. Seedhom. 2001. "Mechanical Behaviour of Articular Cartilage under Tensile Cyclic Load."

Rheumatology 40 (12): 1337–1345. doi:10.1093/rheumatology/40.12.1337.

Bernard, B. P., and V. Putz-Anderson. 1997. "Musculoskeletal Disorders and Workplace Factors; a Critical Review of Epidemiologic Evidence for Work-Related Musculoskeletal Disorders of the Neck, Upper Extremity, and Low Back." National Institute for Occupational Safety and Health Publication No. 97B141. https://www.cdc.gov/niosh/docs/97-141/default.html.

Bongers, P. M., A. M. Kremer, and J. T. Laak. 2002. "Are Psychosocial Factors, Risk Factors for Symptoms and Signs of the Shoulder, Elbow, or Hand/Wrist?: A Review of the Epidemiological Literature." *American Journal of Industrial Medicine* 41 (5): 315–342. doi:10.1002/ajim.10050.

Brinckmann, P., M. Biggemann, and D. Hilweg. 1988. "Fatigue Fracture of Human Lumbar Vertebrae." *Clinical Biomechanics* 3: i–S23. doi:10.1016/S0268-0033(88)80001-9.

Brookham, R. L., J. M. Wong, and C. R. Dickerson. 2010. "Upper Limb Posture and Submaximal Hand Tasks Influence Shoulder Muscle Activity." *International Journal of Industrial Ergonomics* 40 (3): 337–344. doi:10.1016/j.ergon.2009.11.006.

Bureau of Labor Statistics. 2014. "Type of injury or illness and body parts affected by nonfatal injuries and illnesses in 2014." https://www.bls.gov/opub/ted/2015/type-of-injury-or-illness-and-body-parts-affected-by-nonfatal-injuries-and-illnesses-in-2014.htm

Bureau of Labor Statistics. 2015. "Nonfatal Occupational Injuries and Illnesses Requiring Days Away from Work, 2014." Accessed 25 January 2019.

Callaghan, J. P., S. J. Howarth, and T. A. Beach. 2011. "Validation of Occupational Estimates of Cumulative Low-Back Load." *Occupational Ergonomics* 10 (3): 113–124.

De Zwart, B. C. H., M. H. W. Frings-Dresen, and Å. Kilbom. 2000. "Gender Differences in Upper Extremity Musculoskeletal Complaints in the Working Population." *International Archives of Occupational and Environmental Health* 74 (1): 21–30. doi:10.1007/s004200000188.

Dickerson, C. R., A. C. McDonald, and J. N. Chopp-Hurley. 2020. "Between Two Rocks and in a Hard Place: Reflecting on the Biomechanical Basis of Shoulder Occupational Musculoskeletal Disorders." *Human Factors* 0018720819896191.

Gallagher, S., and J. R. Heberger. 2013. "Examining the Interaction of Force and Repetition on Musculoskeletal Disorder Risk: A Systematic Literature Review." *Human Factors* 55 (1): 108–124. doi:10.1177/0018720812449648.

Gallagher, S., and M. C. Schall Jr, 2017. "Musculoskeletal Disorders as a Fatigue Failure Process: Evidence, Implications and Research Needs." *Ergonomics* 60 (2): 255–269. doi:10.1080/00140139.2016.1208848.

Gallagher, S., M. C. Schall Jr, R. F. Sesek, and R. Huangfu. 2018. "An Upper Extremity Risk Assessment Tool Based on Material Fatigue Failure Theory: The Distal Upper Extremity Tool (DUET)." *Human Factors: The Journal of the Human Factors and Ergonomics Society* 60 (8): 1146–1162. doi:10.1177/0018720818789319.

Gallagher, S., R. F. Sesek, M. C. Schall Jr, and R. Huangfu. 2017. "Development and Validation of an Easy-to-Use Risk Assessment Tool for Cumulative Low Back Loading: The Lifting Fatigue Failure Tool (LiFFT)." *Applied Ergonomics* 63: 142–150. doi:10.1016/j.apergo.2017.04.016.

Gallagher, S., W. S. Marras, A. S. Litsky, and D. Burr. 2005. "Torso Flexion Loads and the Fatigue Failure of Human Lumbosacral Motion Segments." *Spine* 30 (20): 2265–2273.

Hanvold, T. N., M. Wærsted, A. M. Mengshoel, E. Bjertness, and K. B. Veiersted. 2015. "Work with Prolonged Arm Elevation as a Risk Factor for Shoulder Pain: A Longitudinal Study among Young Adults." *Applied Ergonomics* 47: 43–51. doi:10.1016/j.apergo.2014.08.019.

Harris-Adamson, Carisa, Ellen A. Eisen, Jay Kapellusch, Arun Garg, Kurt T. Hegmann, Matthew S. Thiese, Ann Marie Dale, Bradley Evanoff, Susan Burt, Stephen Bao, Barbara Silverstein, Linda Merlino, Fred Gerr, and David Rempel. 2015. "Biomechanical Risk Factors for Carpal Tunnel Syndrome: A Pooled Study of 2474 Workers." *Occupational and Environmental Medicine* 72 (1): 33–41. doi:10.1136/oemed-2014-102378.

Herin, F., M. Vézina, I. Thaon, J. M. Soulat, and C. Paris. 2012. "Predictors of Chronic Shoulder Pain after 5 Years in a Working Population." *PAIN®* 153 (11): 2253–2259.

Hignett, S., and L. McAtamney. 2000. "Rapid Entire Body Assessment (REBA)." *Applied Ergonomics* 31 (2): 201–205. doi:10.1016/S0003-6870(99)00039-3.

Jäger, M., C. Jordan, A. Luttmann, W. Laurig, and Dolly Group. 2000. "Evaluation and Assessment of Lumbar Load during Total Shifts for Occupational Manual Materials Handling Jobs within the Dortmund Lumbar Load Study–DOLLY." *International Journal of Industrial Ergonomics* 25 (6): 553–571. doi:10.1016/S0169-8141(99)00043-8.

Janowitz, Ira L., Marion Gillen, Greg Ryan, David Rempel, Laura Trupin, Louise Swig, Kathleen Mullen, Reiner Rugulies, and Paul D. Blanc. 2006. "Measuring the Physical Demands of Work in Hospital Settings: Design and Implementation of an Ergonomics Assessment." *Applied Ergonomics* 37 (5): 641–658. doi:10.1016/j.apergo.2005.08.004.

Kiss, P., M. Meester, A. Kruse, B. Chavée, and L. Braeckman. 2012. "Neck and Shoulder Complaints in Computer Workers and Associated Easy to Assess Occupational Factors-A Large-Scale Cross-Sectional Multivariate Study." *International Archives of Occupational and Environmental Health* 85 (2): 197–206. doi:10.1007/s00420-011-0645-4.

Larsson, B., K. Søgaard, and L. Rosendal. 2007. "Work Related Neck–Shoulder Pain: A Review on Magnitude, Risk Factors, Biochemical Characteristics, Clinical Picture and Preventive Interventions." *Best Practice & Research. Clinical Rheumatology* 21 (3): 447–463. Vol. No. doi:10.1016/j.berh.2007.02.015.

Linaker, C. H., and K. Walker-Bone. 2015. "Shoulder Disorders and Occupation." *Best Practice & Research. Clinical Rheumatology* 29 (3): 405–423. doi:10.1016/j.berh.2015.04.001.

Lipps, D. B., E. M. Wojtys, and J. A. Ashton-Miller. 2013. "Anterior Cruciate Ligament Fatigue Failures in Knees Subjected to Repeated Simulated Pivot Landings." *The American Journal of Sports Medicine* 41 (5): 1058–1066. doi:10.1177/0363546513477836.

McAtamney, L., and E. N. Corlett. 1993. "RULA: A Survey Method for the Investigation of Work-Related Upper Limb Disorders." *Applied Ergonomics* 24 (2): 91–99. doi:10.1016/0003-6870(93)90080-S.

Mitchell, C., A. Adebajo, E. Hay, and A. Carr. 2005. "Shoulder Pain: Diagnosis and Management in Primary Care." *BMJ*

(Clinical Research Ed.) 331 (7525): 1124–1128. doi:10.1136/bmj.331.7525.1124.

National Occupational Research Agenda for Musculoskeletal Health. 2019. Accessed 25 January 2019. https://www.cdc.gov/nora/councils/mus/pdfs/National-Occupational-Research-Agenda-for-Musculoskeletal-Health-October-2018.pdf

Norman, R., R. Wells, P. Neumann, J. Frank, H. Shannon, and M. Kerr. 1998. "A Comparison of Peak vs Cumulative Physical Work Exposure Risk Factors for the Reporting of Low Back Pain in the Automotive Industry." *Clinical Biomechanics* 13 (8): 561–573. doi:10.1016/S0268-0033(98)00020-5.

Occupational Safety and Health Administration. 2014. "Prevention of Musculoskeletal Disorders." Accessed 25 January 2019.

Padula, R. S., M. L. C. Comper, E. H. Sparer, and J. T. Dennerlein. 2017. "Job Rotation Designed to Prevent Musculoskeletal Disorders and Control Risk in Manufacturing Industries: A Systematic Review." *Applied Ergonomics* 58: 386–397. doi:10.1016/j.apergo.2016.07.018.

Pope, D. P., P. R. Croft, C. M. Pritchard, A. J. Silman, and G. J. Macfarlane. 1997. "Occupational Factors Related to Shoulder Pain and Disability." *Occupational and Environmental Medicine* 54 (5): 316–321. doi:10.1136/oem.54.5.316.

Schechtman, H., and D. L. Bader. 1997. "In Vitro Fatigue of Human Tendons." *Journal of Biomechanics* 30 (8): 829–835. doi:10.1016/S0021-9290(97)00033-X.

Sesek, R.F. 1999. "Evaluation and Refinement of Ergonomic Survey Tools to Evaluate Worker Risk of Cumulative Trauma Disorders." Dissertation, Department of Mechanical Engineering, University of Utah.

Shanahan, E. M., and R. Sladek. 2011. "Shoulder Pain at the Workplace." *Best Practice & Research. Clinical Rheumatology* 25 (1): 59–68. doi:10.1016/j.berh.2011.01.008.

Stephens, R. I., A. Fatemi, R. R. Stephens, and H. O. Fuchs. 2001. *Metal Fatigue in Engineering*. 2nd ed. New York: John Wiley and Sons, 472. pp.

Takala, Esa-Pekka, Irmeli Pehkonen, Mikael Forsman, Gert-Åke Hansson, Svend Erik Mathiassen, W Patrick Neumann, Gisela Sjøgaard, Kaj Bo Veiersted, Rolf H. Westgaard, and Jørgen Winkel. 2010. "Systematic Evaluation of Observational Methods Assessing Biomechanical Exposures at Work." *Scandinavian Journal of Work, Environment & Health* 36 (1): 3–24. doi:10.5271/sjweh.2876.

Thornton, G. M., T. D. Schwab, and T. R. Oxland. 2007. "Cyclic Loading Causes Faster Rupture and Strain Rate than Static Loading in Medial Collateral Ligament at High Stress." *Clinical Biomechanics* 22 (8): 932–940. doi:10.1016/j.clinbiomech.2007.05.004.

Van Der Windt, D. A., E. Thomas, D. P. Pope, A. F. De Winter, G. J. Macfarlane, L. M. Bouter, and A. J. Silman. 2000. "Occupational Risk Factors for Shoulder Pain: A Systematic Review." *Occupational and Environmental Medicine* 57 (7): 433–442. doi:10.1136/oem.57.7.433.

Van Rijn, R. M., B. M. Huisstede, B. W. Koes, and A. Burdorf. 2010. "Associations between Work-Related Factors and Specific Disorders of the Shoulder—A Systematic Review of the Literature." *Scandinavian Journal of Work, Environment & Health* 36 (3): 189–201. doi:10.5271/sjweh.2895.