An Upper Extremity Risk Assessment Tool Based on Material Fatigue Failure Theory: The Distal Upper Extremity Tool (DUET)

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Objective: Musculoskeletal tissues repeatedly loaded in vitro fail in accordance with material fatigue failure theory, and there is evidence to suggest that the same process occurs in vivo. The current paper presents a new upper extremity risk assessment tool, the Distal Upper Extremity Tool (DUET), predicated on material fatigue failure theory.

Methods: DUET requires an estimate of force exertion level and the number of repetitions performed to derive estimates of damage and probabilities of experiencing a distal upper extremity outcome. Damage accrued over multiple tasks may be summed to estimate the cumulative damage (CD) accrued over a workday. Validation of this tool was performed using five distal upper extremity (DUE) outcomes (involving medical visits and pain) from an existing epidemiological database involving data from six automotive manufacturing plants. Logistic regression was used to assess the association of the log of the DUET CD measure to DUE outcomes.

Results: Results demonstrated that the log of the DUET CD measure was highly associated with all five DUE outcomes in both crude analyses and those adjusted for site, age, gender, and body mass index ($p < .01$). A model relating the continuous DUET log CD score to the probability of the DUE outcome Injury + Pain Last Year was developed, which demonstrated a significant dose-response relationship.

Conclusions: Results suggest that fatigue failure–based risk assessment techniques are highly associated with DUE outcomes and provide support for the notion that an underlying fatigue failure process may be involved in the development of upper extremity musculoskeletal disorders.

Keywords: job risk assessment, biomechanics, anthropometry, epidemiology, musculoskeletal system, musculoskeletal disorders, cumulative trauma disorders, tissue loading, upper extremity, fatigue failure

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INTRODUCTION

Musculoskeletal disorders (MSDs) of the distal upper extremity (DUE) are prevalent in the working world and have substantial economic costs (Dale et al., 2013; Descatha, Leclerc, Chastang, & Roquelaure, 2003; Gerr et al., 2002; Silverstein et al., 2010; Tanaka, Petersen, & Cameron, 2001). Carpal tunnel syndrome (CTS), for example, was recently observed to afflict 7.8% of 4,321 primarily industrial workers from a pooled multicenter cohort (Dale et al., 2013). Medical treatment of CTS has been estimated to cost over $2 billion annually (Falkiner & Myers, 2002; Stapleton, 2006). Indirect costs such as lost worktime and job change may be substantially greater (Faucett, Blanc, & Yelin, 2000; Foley, Silverstein, & Polissar, 2007).

Several risk factors have been associated with an increased risk of DUE MSDs, including certain personal characteristics and psychosocial stressors (Bao et al., 2016; Gerr et al., 2013; Harris-Adamson et al., 2013). Exposure to physical risk factors such as high force, non-neutral working postures, and repetition are well-known risk factors for MSDs (da Costa & Vieira, 2010; National Research Council & Institute of Medicine, 2001; National Institute for Occupational Safety and Health, 1997). Recent evidence from a prospective study of 2,474 service and production workers suggests that interactions of these risk factors demonstrate a strong association with incident CTS (Harris-Adamson et al., 2015). Such a finding is consistent with the notion that DUE MSDs might be the result of a material fatigue failure process (Gallagher & Heberger, 2013; Gallagher & Schall, 2017). Furthermore, cadaveric studies demonstrate that musculoskeletal tissues incur damage by fatigue failure, animal models have shown that fatigue failure occurs in vivo, and tissue pathology studies exhibit results consistent with a fatigue failure process (Gallagher & Schall, 2017).

Several tools for evaluating the risk of occupationally related upper extremity disorders exist, including the Strain Index (SI; Moore & Garg, 1995), Threshold Limit Value for Hand Activity Level (TLV for HAL; American Conference of Government Industrial Hygienists, 2013), and Rapid Upper Limb Assessment (RULA; McAtamney & Corlett, 1993). While the TLV for HAL and SI have been associated with increased MSD risk in recently completed prospective cohort studies (Bonfiglioi et al., 2013; Burt et al., 2013; Garg et al., 2012; Kapellusch, Garg, Hegmann, Thiese, & Malloy, 2014), these risk assessment tools do not provide a simple means to assess multiple task jobs. Such methods are important due to the prevalence of multitask jobs in industry (Leider, Boschman, Frings-Dresen, & van der Molen, 2015; Padula, Comper, Sparer, & Dennerlein, 2017). Extensions to the SI have recently been proposed to address this need (Garg, Moore, & Kapellusch, 2017). However, to this point, no DUE risk assessment tools have incorporated the precepts of material fatigue failure theory to evaluate MSD risk. Since tissue damage development has been shown to follow fatigue failure principles (e.g., Brinckmann, Biggemann, & Hilweg, 1988; Schechtman & Bader, 1997), it would seem reasonable to examine whether DUE outcomes also follow such principles.

This paper introduces a new DUE risk assessment tool based on fatigue failure principles, the Distal Upper Extremity Tool (DUET). DUET is designed to provide a measure of *daily exposure* to DUE risk factors and can evaluate mono-task jobs or exposures associated with multiple tasks. The tool requires only two inputs per task: a force exertion assessment and the number of repetitions performed. The goals of this paper are to: (1) develop a cumulative damage metric based on material fatigue failure theory, (2) validate the cumulative damage metric, (3) develop a risk model based on validation results, and (4) describe and give examples of the use of the DUET.

METHODS

Development of the DUET Cumulative Damage Metric

Fatigue failure theory stipulates that the development of damage in a material is the result of repeated loading and unloading at a stress below the material's ultimate stress (the stress level causing failure in one cycle). The relationship between stress magnitude and the number of cycles resulting in damage is exponential, such that small stresses may be tolerated for many thousands of cycles, but high stresses may cause failure in very few cycles. Cumulative damage (CD) estimates can be developed using validated methods that correlate very well with MSD outcomes (Gallagher, Sesek, Schall, & Huangfu, 2017). Readers interested in a more in-depth background on fatigue failure are referred to Gallagher and Schall (2017).

Determining the number of repetitions experienced by a worker is comparatively easy; however, estimating the stress experienced by tissues is more complicated. To obtain an estimate, we assume that the cross-sectional area of the tissue remains constant. Thus, a method of estimating the force experienced by the tissues is all that is necessary. The authors have employed the OMNI Perceived Exertion Scale for Resistance Exercise (OMNI-RES) for this purpose (Lagally & Robertson, 2006; Robertson et al., 2003), which provides a method of quickly estimating forces experienced by the DUE during occupational tasks. The OMNI-RES scale rates exertion on a 0 to 10 scale, as illustrated in Table 1. This scale has demonstrated strong construct validity, indicating that it measures the same properties of exertion as the Borg Rating or Perceived Exertion Scale with respect to quantification of resistance exercise (Lagally & Robertson, 2006; Morishita, Yamauchi, Fujisawa, & Domen, 2013). It is recommended that trained observers provide this estimate; however, worker estimates may also be obtained for this purpose.

In DUE MSDs, tendons are a tissue of primary concern (Lavagnino et al., 2015; National Research Council & Institute of Medicine, 2001; Ranney, Wells, & Moore, 1995). Accordingly, we used data on in vitro fatigue failure of tendons to develop a weighting scheme regarding the damage per cycle (DPC) at various levels of force/stress. Data were derived from a study of fatigue failure of the human extensor digitorum longus at different levels of ultimate tensile strength (Schechtman & Bader, 1997). The

TABLE 1: OMNI Perceived Exertion Scale for Resistance Exercise Scale (OMNI-RES) and Associated Estimates of Percentage of Tendon Ultimate Stress, Cycles to Failure, and Damage Per Cycle Weights Derived From Schechtman and Bader (1997) Data

OMNI-RES Scale	Estimated Percentage of Tendon Ultimate Stress	Estimated Cycles to Failure	Damage Per Cycle Weighting
0 = *very easy*	3.6	3,842,605	0.00000026
1	7.1	2,231,607	0.00000045
2 = *easy*	14.3	729,651	0.00000137
3	21.4	242,301	0.00000413
4 = *somewhat easy*	28.6	79,223	0.00001262
5	35.7	26,308	0.00003801
6 = *somewhat hard*	42.9	8,602	0.00011625
7	50.0	2,856	0.00035014
8 = *hard*	57.1	949	0.00105374
9	64.3	310	0.00322581
10 = *very hard*	71.4	103	0.00970874

relationship of the percentage of ultimate stress level versus median fatigue life was expressed by the following equation:

$$S = 101.25 - 14.83 \times log(N), \qquad (1)$$

where S represents the percentage of tensile stress (relative to ultimate tensile stress), and N represents cycles to failure. In using this relationship, we were mindful that the strain at a maximum voluntary contraction (MVC) is not equivalent to strain that would cause one cycle tendon failure (approximately 8%–10% strain; Wren, Yerby, Beaupre, & Carter, 2001). Kubo, Teshima, Ikebukuro, Hirose, and Tsunoda (2014) suggest that the average tendon strain at 100% MVC across two tendons tested is approximately 6.6%. Compared to the 8% to 10% tendon failure strain range, the strain at 100% MVC is approximately 73% of failure strain. The reciprocal (1/0.73) of 1.36 suggests that failure strain is approximately 1.4 times the strain observed at 100% MVC. Thus, we scaled cycles to failure such that the one cycle failure value (i.e., ultimate stress) was 1.4 times the maximum exertion force on the OMNI-RES scale (Table 1).

Based on this relationship, the DPC for various levels of stress was determined. DPC represents the proportion of damage occurring in one cycle at a given stress level. These data were related to force levels of the OMNI-RES scale to provide a weighting for the effect of repetition at various levels of force (see Table 1).

Estimating Cumulative Damage Using the DUET Framework

Only two inputs (per task) are required for a DUET analysis. These include an estimate of task force exertion and the daily repetitions performed for that task. Based on the force level, the tool assigns a DPC value, which is then multiplied by daily repetitions. If a job involves only one task (i.e., mono-task), the selected force level is multiplied by the associated DPC to obtain an estimated CD, representing a "daily dose" of exposure. If a worker performs multiple DUE tasks per workday, each individual task can be assessed as previously described, and the CD for every task may be summed to obtain the "daily dose" of CD per Equation 2:

$$Total\ CD = DPC_{Task1} * n_{Task1} + DPC_{Task2} * n_{Task2} + \cdots + DPC_{Task\ j} * n_{Task\ j}, \qquad (2)$$

where CD is cumulative damage, DPC represents the damage per cycle, n represents the number of repetitions per task, and j represents the total number of tasks.

In highly complex jobs, or data collected for an epidemiological study, we recommend that a task analysis be performed to define work tasks that comprise a job. Work-sampling methods can be used to help ensure that all relevant exposures are captured. The number of repetitions that should be observed will depend on the variability of the tasks performed (Waters & Dick, 2015). Marras, Allread, and Ried (1999) have suggested observing 7 to 10 cycles of a given task. However, this may not be possible for infrequent tasks (which might be the most physically demanding). As a general rule, the more frequent a task, the more cycles should be observed to get a representative assessment. In general use, task analysis and work sampling techniques may not be required; however, it is important to obtain exposure estimates for every task performed during the workday.

Validation of the DUET Cumulative Damage Metric and Development of the DUET Risk Model

To validate the DUET CD metric, we used data from an epidemiological study involving a large automotive manufacturer (Sesek, 1999). The database included historical injury data for the analyzed jobs and symptom interviews for 1,022 participants. Data collection was performed from February 1998 through September 1999 at six manufacturing plants. A total of 772 participants working in 501 unique jobs were analyzed for DUE risk. Five subsets, each having different case/control definitions, were analyzed (see Table 2).

Ethical considerations. This research complied with the tenets of the Declaration of Helsinki and was approved by the Institutional Review Boards at University of Utah and University of South Florida. All participants were apprised of study procedures and signed informed consent forms prior to data collection. Participants were apprised of their right to withdraw from the study at any time. All participants volunteered and did not receive financial inducement of any kind.

Study design. The epidemiology study used for DUET validation was cross-sectional. The study was conducted from February 1998 to October 1999 at six component and assembly plants of a major automotive manufacturer. The epidemiology study enrolled 1,022 employees representing a broad cross-section of automotive manufacturing employees. Females represented 27.3% of the overall workforce. Employees ranged in age from 20 to 70 years, with a mean age of 41.0 years. Employee heights ranged from 147 to 203 cm, with a mean of 174.8 cm. The overall average BMI) was 27.5 kg/m^2 and ranged from 24.3 kg/m^2 to 30.3 kg/m^2, and the average employee was 84.8 kg. The number of participants assessed for DUE outcomes ranged from 441 to 772, depending on the case-control definition tested. Participant details by specific outcomes are described in Table 2.

Case and control definitions. The five DUE outcomes included injury, injury plus pain today, injury plus pain last year, pain today, and pain last year. Injury was defined as a job where a first-time office visit (FTOV) for DUE symptoms occurred during the past year. If two participants were analyzed on this job, the exposure assessment for each participant would be associated with a positive DUE (injury) outcome. Participants undergoing exposure assessment for this job might not have been among those experiencing injury. Controls were participants on jobs *not* having had a reported injury (FTOV) during the past year. Outcomes involving injury plus pain were treated similarly. In these circumstances, participants on jobs having a recorded FTOV during the past year *plus* participant reported pain (>15 mm visual analog scale [VAS] current or past year) were considered cases, and individuals on jobs without an FTOV *plus* no current pain or pain last year (<15 mm VAS) were controls. Outcomes of pain today or pain last year were considered positive if participants reported pain above 15 mm on a 100 mm VAS scale over the relevant time period. Controls for pain only outcomes were those not reporting pain >15 mm VAS over those time periods.

Participant inclusion/exclusion criteria. Participants were included if they performed well-defined cyclic jobs, had been on the current job >30 days, and agreed to be videotaped during the performance of their regular job. Participants were excluded if they worked in noncyclic, ill-defined jobs such as maintenance activities.

TABLE 2: Demographic and Outcome Characteristics for the Grips and Deviations Repetition Condition

Outcomes	All Study Participants	Cases	Non-Cases
Injury (first time office visit for distal upper extremity symptoms)			
Total *N*	771	293	478
Age group, *n* (%)			
≤40	331 (42.9)	160 (54.6)	171 (35.8)
>40	436 (56.5)	131 (44.7)	305 (63.8)
Not reported	4 (0.5)	2 (0.7)	2 (0.4)
Sex, *n* (%)			
Female	219 (28.4)	92 (31.4)	127 (26.6)
Male	546 (70.8)	198 (67.6)	348 (72.8)
Not reported	6 (0.8)	3 (1.0)	3 (0.6)
BMI, *n* (%)			
≤30	565 (73.3)	224 (76.5)	341 (71.3)
>30	199 (25.8)	68 (23.2)	131 (27.4)
Not reported	7 (0.9)	1 (0.3)	6 (1.3)
Injury + pain today			
Total *N*	470	123	347
Age group, *n* (%)			
≤40	187 (39.8)	69 (56.1)	118 (34.0)
>40	280 (59.6)	53 (43.1)	227 (65.4)
Not reported	3 (0.6)	1 (0.8)	2 (0.6)
Sex, *n* (%)			
Female	130 (27.7)	50 (40.7)	80 (23.1)
Male	336 (71.5)	71 (57.7)	265 (76.4)
Not reported	4 (0.8)	2 (1.6)	2 (0.6)
BMI, *n* (%)			
≤30	345 (73.4)	92 (74.8)	253 (72.9)
>30	120 (25.5)	31 (25.2)	89 (25.6)
Not reported	5 (1.1)	0 (0.0)	5 (1.4)
Injury + pain last year			
Total *N*	441	188	253
Age group, *n* (%)			
≤40	185 (42.0)	104 (55.3)	81 (32.0)
>40	254 (57.6)	83 (44.1)	171 (67.6)
Not reported	2 (0.5)	1 (0.5)	1 (0.4)
Sex, *n* (%)			
Female	109 (24.7)	65 (34.6)	44 (17.4)
Male	328 (74.4)	121 (64.4)	207 (81.8)
Not reported	4 (1.1)	2 (1.1)	2 (0.8)
BMI, *n* (%)			
≤30	328 (74.4)	140 (74.5)	188 (74.3)
>30	110 (24.9)	48 (25.5)	62 (24.5)
Not reported	3 (0.7)	0 (0.0)	3 (1.2)

(continued)

TABLE 2: (continued)

Outcomes	All Study Participants	Cases	Non-Cases
Pain today			
Total *N*	772	254	518
Age group, *n* (%)			
≤40	331 (42.9)	122 (48.0)	209 (40.3)
>40	437 (56.6)	131 (51.6)	306 (59.1)
Not reported	4 (0.5)	1 (0.4)	3 (0.6)
Sex, *n* (%)			
Female	219 (28.4)	97 (38.2)	122 (23.6)
Male	547 (70.9)	154 (60.6)	393 (75.9)
Not reported	6 (0.8)	3 (1.2)	3 (0.6)
BMI, *n* (%)			
≤30	566 (73.3)	180 (69.7)	386 (74.5)
>30	199 (25.8)	73 (29.9)	126 (24.3)
Not reported	7 (0.9)	1 (0.4)	6 (1.2)
Pain last year			
Total *N*	772	414	358
Age group, *n* (%)			
≤40	331 (42.9)	194 (46.9)	137 (38.3)
>40	437 (56.6)	218 (52.7)	219 (61.2)
Not reported	4 (0.5)	2 (0.5)	2 (0.6)
Sex, *n* (%)			
Female	219 (28.4)	148 (35.7)	71 (19.8)
Male	547 (70.9)	263 (63.5)	284 (79.3)
Not reported	6 (0.8)	3 (0.7)	3 (0.8)
BMI, *n* (%)			
≤30	566 (73.3)	294 (71.0)	272 (76.0)
>30	199 (25.8)	117 (28.3)	82 (22.9)
Not reported	7 (0.9)	3 (0.7)	4 (1.1)

Further exclusions included those who chose to opt out for any reason. In most such cases, other participants were observed performing the selected job.

Exposure assessment. All jobs were videotaped, and the analysis team reviewed hand activities (grips and deviations) by randomly sampling videotaped jobs. Teams of two to three trained analysts agreed on a consensus count of task motions. Some jobs had multiple participants assessed; for others, only one participant may have been assessed. Jobs consisted of at least one and up to four DUE tasks. Exertion levels for each task were obtained using the SI exertion scale. Two methods were used to assign OMNI-RES categories to the SI scale. The first was to match verbal anchors as closely as possible. For this method SI intensity ratings 1 to 5 were assigned OMNI-RES scale values of 2, 6, 8, 9, and 10. The second method was to match relative scale values, where SI intensity ratings 1 to 5 were assigned OMNI-RES levels 2, 4, 6, 8, and 10, respectively. For jobs having multiple DUE tasks, the CD associated with each was summed to develop a daily dose of exposure, per Equation 2. Table 3 provides examples of three multitask jobs from the database to illustrate calculation of CD estimates.

TABLE 3: Examples of Three Multitask Jobs From the Epidemiology Database (Each Comprised of Multiple DUE Tasks) Demonstrating How the Daily Dose of Cumulative Damage Was Calculated

	Efforts/ Minute	OMNI-RES Intensity	Damage/Effort	Damage/Hour
Left-hand door body seal				
1. Prep/place sealant	3.75	2	0.00000137	0.00030825
2. Guide panel	1.5	4	0.00001262	0.0011385
3. Lift/place panel	4.5	6	0.00011625	0.0313875
			Total damage/hour →	0.03283155
			Typical work duration →	10
			Total damage/day →	0.3283155
OHC engine cover				
1. Grab/place outer belt cover	10	2	0.00000137	0.000822
2. Drive screw	4	2	0.00000137	0.0003288
			Total damage/hour →	0.0011508
			Typical work duration →	9
			Total damage/day →	0.0103572
Build disk assembly				
1. Get/place part	2.73	2	0.00000137	0.000224406
2. Assemble	30	2	0.00000137	0.002466
3. Drive screws	5.4545	4	0.00001262	0.004130147
4. Place completed part	2.7273	2	0.00000137	0.000224184
			Total damage/hour →	0.007044737
			Typical work duration →	10
			Total damage/day →	0.07044737

Note. OMNI-RES = OMNI Perceived Exertion Scale for Resistance Exercise; DUE = distal upper extremity; OHC = over head cam.

Statistical analyses. An analysis of 2 × 2 contingency tables using a CD cut point of 0.03 was performed to discriminate between high and low risk jobs for each outcome. The cut point was based on data suggesting a collagen turnover rate in tendon of 2% to 3% per day (Kjaer et al., 2005). Thus, the 3% cut point was taken to approximate daily tendon healing capacity, above which CD would accrue. Chi-square statistics, odds ratios, accuracy, sensitivity, specificity, and positive and negative predictive values were calculated for each outcome. For this analysis, three definitions of repetition were analyzed, including *deviations alone, grips alone*, and *deviations+grips*. In addition, we analyzed the magnitude of pain reported by participants (past year and current) with the log CD measure using linear regression. For this analysis, the average reported pain (past year and current) per decile was regressed against the log CD measure. Type I error rates were 0.05 for all analyses.

Binary logistic regression was used to ascertain both crude and adjusted odds ratios associated with the log of the continuous DUET CD measure. Covariates included sites (6), sex, age, and BMI. Age and BMI were dichotomized, with split points of 40 years for age and a BMI value of 30. Regression equations from unadjusted analyses were used to determine the relationship between the log of the DUET CD measure and the probability of a positive outcome using the following equation:

$$P(Event) = \exp(Y') / (1 + \exp(Y')), \quad (3)$$

where $Y' = \beta_0 + \beta_1 \times Log\ CD$ (derived from logistic regression). Thus, this regression equation provided the means by which to estimate the probability of a DUE outcome for each value of the DUET CD metric. This information formed the basis for the DUET Risk Model.

RESULTS

Analysis of a DUET CD Cut Point of 0.03

Table 4 provides an analysis of the odds ratios (OR; with 95% CI), sensitivity, specificity, positive and negative predictive values, and accuracy for a DUET daily dose CD cut point of 0.03 for DUE outcomes. All three definitions of repetition demonstrated significant ORs for all outcomes.

Association Between CD Metric and Reported Pain

The log of the DUET CD metric was significantly associated with magnitude of VAS ratings for both past year and current pain reports. For pain last year, the linear regression was significant, $F(1, 8) = 8.60$, $p = .019$, $R^2 = 51.80\%$, per Equation 4:

$$\text{Average Pain Past Year} = 45.24 + 5.898 * Log\ CD. \quad (4)$$

A similar relationship was observed between pain today and the log CD measure, $F(1, 8) = 9.45$, $p = .015$, $R^2 = 54.15\%$. The regression is shown in Equation 5:

$$\text{Average Pain Today} = 17.86 + 2.2867 * Log\ CD. \quad (5)$$

Logistic Regression Results

Tables 5 and 6 demonstrate that the DUET log CD measure exhibited strong relationships with all five DUE outcomes in logistic regression analyses for both verbal anchor and scale-based OMNI-RES weighting methods, respectively. Chi-square values were significant for all unadjusted analyses ($p < .01$) and all but one adjusted analysis ($p < .01$). ORs for the log CD measure in adjusted analyses ranged from 1.140 to 1.616 for the verbal anchor weighting method and 1.283 to 2.089 for the scale-based weighting method. Interpretation of these OR values would be that for every order of magnitude increase in the DUET log CD measure, there would be an increase in probability of experiencing a DUE outcome equal to the OR. Site was significant in all adjusted models, and gender was included as a significant covariate for outcomes involving pain. Neither age nor BMI were identified as a significant covariate in adjusted logistic regression models.

DUE Probability Estimates Based on DUET Log CD Measure

Logistic regression equations derived from unadjusted analyses were used to estimate probabilities of various DUE outcomes based on the DUET Log CD measure. For the DUE outcome injury plus pain last year, the following regression equation was obtained:

$$Y' = 0.573 + 0.747 * Log\ CD, \quad (6)$$

where Y' represents the response of the outcome variable, and Log CD represents the value of the log of the DUET CD measure. Table 5 provides additional statistical details for this logistic regression result. Estimated probabilities of the DUE outcome based on the DUET log CD value can be calculated using:

$$P(Outcome) = \exp(Y') / (1 + \exp(Y')), \quad (7)$$

where Y' is derived from Equation 6. Figure 1 illustrates the results of this analysis. This DUE outcome demonstrates a dose-response relationship such that the outcome probability is approximately 5% at a log CD of about –5.0 and rises to approximately 90% at a log CD value of 2.0 (refer to Table 5 for additional statistical results for this outcome).

THE DUET RISK ASSESSMENT TOOL

The Web-based version of the DUET risk assessment tool is shown in Figures 2 and 3. As can be seen, the interface is straightforward, requiring only the rating of perceived

TABLE 4: Odds Ratios and Related Measures for DUET for CD >0.03 for DUE MSD Outcomes in the Automotive Database (Sesek, 1999)

	Injury Versus None	Injury Plus Pain Today Versus Neither	Injury Plus Pain Past Year Versus Neither	Pain Today Versus None	Pain Past Year Versus None
Deviations only					
Chi-square	16.89	21.38	26.89	9.15	15.71
p	<.001	<.001	<.001	.002	<.001
OR	1.85	2.77	2.89	1.60	1.77
95% CI	1.38, 2.49	1.78, 4.30	1.88, 4.11	1.18, 2.17	1.33, 2.36
Accuracy	56.0	57.8	61.7	53.4	57.3
Prevalence	0.38	0.26	0.42	0.42	0.53
Sensitivity	0.64	0.71	0.67	0.67	0.61
Specificity	0.51	0.53	0.58	0.58	0.53
PPV	0.45	0.35	0.54	0.54	0.60
NPV	0.70	0.84	0.70	0.70	0.55
Grips only					
Chi-square	7.37	19.52	12.92	8.96	6.22
p	.007	<.001	<.001	.003	.013
OR	1.49	2.57	2.00	1.58	1.43
95% CI	1.12, 1.99	1.82, 4.44	1.37, 2.93	1.17, 2.13	1.08, 1.90
Accuracy	56.6	54.1	60.1	58.7	55.7
Prevalence	0.38	0.26	0.42	0.33	0.53
Sensitivity	0.52	0.65	0.58	0.53	0.50
Specificity	0.58	0.59	0.60	0.58	0.59
PPV	0.43	0.35	0.51	0.38	0.58
NPV	0.66	0.82	0.66	0.72	0.51
Grips and deviations					
Chi-square	7.23	14.88	14.85	7.23	7.09
p	.007	<.001	<.001	.007	.008
OR	1.70	2.59	2.27	1.57	1.50
95% CI	1.23, 2.34	1.58, 4.25	1.49, 3.46	1.13, 2.19	1.11, 2.03
Accuracy	51.2	49.4	55.8	48.0	55.5
Prevalence	0.38	0.26	0.42	0.33	0.53
Sensitivity	0.75	0.81	0.77	0.74	0.72
Specificity	0.37	0.38	0.40	0.35	0.37
PPV	0.42	0.32	0.49	0.36	0.56
NPV	0.70	0.85	0.71	0.74	0.54

Note. DUET = Distal Upper Extremity Tool; CD = cumulative damage; DUE = distal upper extremity; MSD = musculoskeletal disorder; OR = odds ratio; PPV, positive predictive value; NPV, negative predictive value.

effort using the OMNI-RES scale (drop-down menu) and the number of daily repetitions to be entered for each task being analyzed. The tool will calculate the CD associated with the task and provide the percentage of the total daily CD associated with that task.

TABLE 5: Crude and Adjusted Odds Ratios Using Total Grips and Deviations for Five DUE Outcomes Versus the Log of the DUET CD Metric as a Continuous Measure (Log CD) Using Scale-Matching Method

Outcome	Analysis	Cases	*N*	Variable	*df*	χ^2	*p*	OR	95% CI
Injury (first-time office visit)	Crude	293	771	Log CD	1	35.02	<.001	1.659	1.391, 1.978
	Adjusted	290	765	Log CD	1	19.88	<.001	1.592	1.289, 1.967
				Site	5	108.62	<.001	Var	Var
				Gender	1	0.33	.565	1.112	0.774, 1.596
				Age	1	0.65	.419	0.863	0.604, 1.233
				BMI	1	1.39	.239	0.796	0.544, 1.165
Injury + pain today	Crude	123	470	Log CD	1	33.75	<.001	2.049	1.573, 2.668
	Adjusted	121	462	Log CD	1	17.08	<.001	1.950	1.400, 2.718
				Site	5	83.08	<.001	Var	Var
				Gender	1	3.44	.064	0.610	0.363, 1.026
				Age	1	0.14	.709	0.905	0.537, 1.526
				BMI	1	0.51	.475	1.235	0.694, 2.197
Injury + pain past year	Crude	188	441	Log CD	1	44.29	<.001	2.111	1.657, 2.689
	Adjusted	186	435	Log CD	1	25.89	<.001	2.089	1.539, 2.836
				Site	5	81.87	<.001	Var	Var
				Gender	1	2.28	.131	0.669	0.398, 1.127
				Age	1	1.13	.288	0.766	0.468, 1.253
				BMI	1	0.52	.470	1.224	0.707, 2.118
Pain today	Crude	254	772	Log CD	1	12.76	<.001	1.359	1.144, 1.614
	Adjusted	250	760	Log CD	1	6.60	.010	1.283	1.058, 1.556
				Site	5	17.64	.003	Var	Var
				Gender	1	11.04	.001	0.562	0.401, 0.788
				Age	1	0.09	.758	1.058	0.741, 1.509
				BMI	1	2.16	.142	1.306	0.916, 1.861
Pain past year	Crude	414	772	Log CD	1	20.89	<.001	1.444	1.229, 1.696
	Adjusted	408	760	Log CD	1	14.53	<.001	1.413	1.179, 1.694
				Site	5	16.08	.007	Var	Var
				Gender	1	16.21	<.001	0.500	0.355, 0.704
				Age	1	0.00	.966	0.993	0.703, 1.402
				BMI	1	2.94	.087	1.350	0.957, 1.904

Note. Scale matching method = Strain Index 1 through 5 = OMNI Perceived Exertion Scale for Resistance Exercise 2, 4, 6, 8, and 10. Adjusted cases are controlled for plant site, age (>40 years), gender (M = 1, F = 0), and BMI (>30). Significant site results are associated with 15 separate ORs that are not shown. Var = various; *N* = total number of participants analyzed; DUET = Distal Upper Extremity Tool; CD = cumulative damage; DUE = distal upper extremity.

Examples of Calculating Cumulative Damage With DUET

The simplest example where DUET can be applied is a mono-task job where a worker performs the same DUE task throughout the workday. Assume the task is performed ten times a minute over a nine-hour daily work period, and force demands are estimated to be a 2 (“Easy”) on the OMNI-RES scale. The estimated CD can be calculated by multiplying the number of efforts/minute (10) by 60 (minutes/hour) and then multiplying the resulting product by

TABLE 6: Crude and Adjusted Odds Ratios Using Total Grips and Deviations for Five DUE Outcomes Versus the Log of the DUET Cumulative Damage Metric as a Continuous Measure (Log CD) Using Verbal Anchor Matching Method

Outcome	Analysis	Cases	N	Variable	df	Chi-sq	*P*	OR	95% CI
Injury (first-time office visit)	Crude	293	771	Log CD	1	29.66	<.001	1.434	1.253, 1.640
	Adjusted	289	759	Log CD	1	21.27	<.001	1.459	1.236, 1.722
				Site	5	114.13	<.001	Var	Var
				Gender	1	0.21	.649	1.088	0.757, 1.564
				Age	1	0.57	.451	0.872	0.610, 1.246
				BMI	1	1.35	.245	0.798	0.545, 1.169
Injury + pain today	Crude	123	470	Log CD	1	23.89	<.001	1.586	1.300, 1.935
	Adjusted	121	462	Log CD	1	11.75	.001	1.530	1.190, 1.968
				Site	5	86.82	<.001	Var	Var
				Gender	1	3.54	.060	0.607	0.362, 1.019
				Age	1	0.20	.655	0.888	0.528, 1.494
				BMI	1	0.51	.473	1.233	0.696, 2.185
Injury + pain past year	Crude	188	441	Log CD	1	32.75	<.001	1.616	1.357, 1.925
	Adjusted	186	435	Log CD	1	21.13	<.001	1.616	1.323, 2.091
				Site	5	85.74	<.001	Var	Var
				Gender	1	2.93	.087	0.634	0.377, 1.069
				Age	1	1.16	.281	0.764	0.468, 1.246
				BMI	1	0.50	.480	1.217	0.706, 2.096
Pain today	Crude	254	772	Log CD	1	6.73	.009	1.188	1.041, 1.356
	Adjusted	250	760	Log CD	1	3.06	.080	1.140	0.983, 1.322
				Site	5	19.31	.002	Var	Var
				Gender	1	11.10	.001	0.561	0.400, 0.787
				Age	1	0.040	.833	1.039	0.728, 1.482
				BMI	1	2.33	.127	1.319	0.926, 1.878
Pain past year	Crude	414	772	Log CD	1	14.08	<.001	1.261	1.116, 1.425
	Adjusted	408	760	Log CD	1	10.62	.001	1.257	1.094, 1.445
				Site	5	17.37	.004	Var	Var
				Gender	1	16.78	<.001	0.494	0.351, 0.696
				Age	1	0.01	.934	0.986	0.698, 1.392
				BMI	1	3.11	.078	1.361	0.965, 1.918

Note. Verbal anchor matching method = Strain Index 1 through 5 = OMNI Perceived Exertion Scale for Resistance Exercise 2, 6, 8, 9, and 10. Adjusted cases are controlled for plant site, age (>40), gender (M = 1, F = 0), and BMI (>30). Significant site results are associated with 15 separate ORs that are not shown. Var = various; *N* = total number of participants analyzed; DUET = Distal Upper Extremity Tool; CD = cumulative damage; DUE = distal upper extremity.

the total hours worked (9) to arrive at the total daily repetitions (5,400). CD is then estimated by multiplying the total repetitions by the DPC estimate associated with the OMNI-RES scale value of 2 (0.00000137), per Table 1. In this scenario, the analysis gives a CD daily dose of 0.0074, which gives an estimated probability of 26.5% of experiencing a DUE disorder.

A major benefit of DUET is that the CD associated with multiple tasks can be easily summed to calculate a daily dose of exposure. Multiple tasks could comprise either several tasks within a single

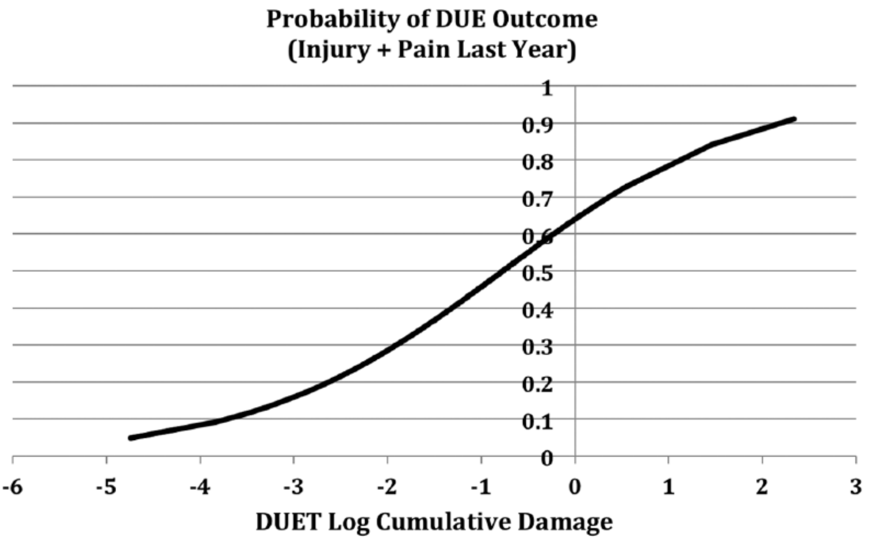

Figure 1. Probability of distal upper extremity outcome injury + pain last year by Distal Upper Extremity Tool log cumulative damage measure.

job or a worker performing a job rotation. A multiple-task DUET analysis is illustrated in Figure 3. In this example, the worker's job involves four distinct DUE tasks. Task 1 is characterized as *easy* on the OMNI-RES scale and is performed 5,184 times per workday. Task 2 is rated *somewhat easy* and has 180 daily repetitions. The third is rated *extremely hard* and is performed 60 times per workday, while the fourth task is rated *easy* and is performed 3,752 times/day. The total CD associated with these four tasks (0.59703) puts the DUE risk at 60.5%. As shown in Figure 3, DUET provides the percentage of total CD associated with each task. In this example, Task 3 is responsible for 97.6% of the total CD and would be a prime candidate for job redesign.

DISCUSSION

The goal of this paper was to develop and present a validated DUE risk assessment tool based on a material fatigue failure process parameterized from the literature of in vitro stress strain tests of tendons. The CD metric was highly associated with increased risk of injury providing contextual validity. The dose-response relationship provides an estimate of injury risk that completes the DUET tool. The DUET tool uses exposure metrics of force and repetition and converts them to tissue dose CD and then to a health outcome (injury/pain) risk.

In DUET, the authors opted to use the OMNI-RES scale (Robertson et al., 2003) rather than the Borg CR-10 scale (Borg, 1990) to estimate force exertion. Examination of the Borg CR-10 reveals an imbalance in the scale in the assessment of easy (0–2 on the scale) versus hard (4–10) exertions. The OMNI-RES scale is symmetrically balanced and provides a wider range for middle-ground estimates of exertion, which was deemed important for this tool. The OMNI-RES scale should be easily accessible to practitioners (perhaps more intuitive than the Borg CR-10).

Dose-response associations were observed for the log CD measure and pain prevalence (OR range = 1.140–1.444) and were even stronger for outcomes involving injury (OR range = 1.434–2.089). It is notable that all but one of the statistical tests (34/35) involving the DUET CD measure was statistically significant. Analyses using a CD cut point of 0.03 (corresponding to an outcome probability of 36.2% in the risk model) for three different definitions of repetition show that each (hand deviations, grips, or the combination of the two) demonstrate significant results using the DUET CD measure, which may

The Distal Upper Extremity Tool

Task #	OMNI-RES Scale	Repetitions (per work day)	Damage (cumulative)	% Total (damage)
1	2: Easy	5400	0.0074	100.0
2	Please select ...	0	0.0	0.0
3	Please select ...	0	0.0	0.0
4	Please select ...	0	0.0	0.0
5	Please select ...	0	0.0	0.0
6	Please select ...	0	0.0	0.0
7	Please select ...	0	0.0	0.0
8	Please select ...	0	0.0	0.0
9	Please select ...	0	0.0	0.0
10	Please select ...	0	0.0	0.0
			Total Cumulative Damage:	0.0074
			Probability of Distal Upper Extremity Outcome (%):	26.5

Reset Calculate

Figure 2. Example of the use of Distal Upper Extremity Tool for a mono-task distal upper extremity job.

The Distal Upper Extremity Tool

Task #	OMNI-RES Scale	Repetitions (per work day)	Damage (cumulative)	% Total (damage)
1	2: Easy	5184	0.0071	1.2
2	4: Somewhat Easy	180	0.00227	0.4
3	10: Extremely Hard	60	0.58252	97.6
4	2: Easy	3752	0.00514	0.9
5	Please select ...	0	0.0	0.0
6	Please select ...	0	0.0	0.0
7	Please select ...	0	0.0	0.0
8	Please select ...	0	0.0	0.0
9	Please select ...	0	0.0	0.0
10	Please select ...	0	0.0	0.0
			Total Cumulative Damage:	0.59703
			Probability of Distal Upper Extremity Outcome (%):	60.5

Reset Calculate

Figure 3. Example of a Distal Upper Extremity Tool multitask distal upper extremity assessment.

provide analysts or researchers flexibility in terms of how repetitions are defined (Table 3).

The authors examined two weighting methods for the Strain Index exertion level scale as well. Like the Borg scale, the Strain Index exertion scale is skewed toward the "hard" end. Thus, the authors performed logistic regression analyses using two weighting schemes. While the current study uses the OMNI-RES values of 2, 4, 6, 8, and 10 for Strain Index 1 through 5 (based on numerical scale values), we also examined a weighting scheme where we matched verbal anchors, where Strain Index 1 through 5 were matched against OMNI-RES categories 2, 6, 8, 9, and 10. Both analyses resulted in significant odds ratios. We believe that the reason that both weighting schemes produced significant findings resulted from the dominant influence of the exponential weighting of the DPC measure.

This is the second tool developed by the authors that uses a material fatigue failure methodology to assess MSD risk. The other tool (the Lifting Fatigue Failure Tool, or LiFFT) estimates the compressive load based on peak load moment of a lift and uses data from spinal motion segment fatigue failure studies (Brinckmann et al., 1988; Gallagher et al., 2007) to apply appropriate DPC weights, which are summed similarly to the current tool (Gallagher et al., 2017). Validation of LiFFT demonstrated significant relationships between the CD measure and seven separate low back outcomes across two epidemiological studies (Gallagher et al., 2017).

The strong association between CD metrics and MSD outcomes for both DUET and LiFFT may reflect the underlying etiology of these disorders. While it has long been recognized that MSDs result from a cumulative trauma process, prior risk assessment tools have not employed primary techniques used to assess the development of cumulative damage due to repetitive stress, a process demonstrated by tissues in vitro (Brinckmann et al., 1988; Gallagher et al., 2007; Schechtman & Bader, 1997).

Some comparisons can be made between DUET and other DUE assessment tools, such as the SI and HAL. All three tools rely on an estimate of force exertion using some rating of perceived effort. Similar to the SI multiplier for exertion intensity, DUET employs a nonlinear weighting for force. However, since DUET provides a continuous measure of CD as a basis for analysis, the results of a DUET assessment can provide an estimated outcome probability for any given value. Such analyses are not currently available with other existing tools. A major benefit of DUET is that the CD associated with multiple tasks can be easily summed using validated fatigue failure procedures. This allows for estimation of a daily dose of exposure and an assessment of the relative contribution of various tasks based on a process that may well reflect how musculoskeletal injuries develop.

Similar to HAL, DUET requires only two inputs per task to conduct a job assessment (a force estimate and repetition count). While HAL simplifies the analysis by using a global estimate of normalized peak force and hand activity, DUET accounts for variations in the frequency of various force levels. One potential advantage of the DUET approach is that force levels are less likely to be overestimated if peak force is rarely observed for a task. Another difference between HAL and DUET is that the hand activity level estimate for HAL may be difficult to estimate when a job is highly repetitive but also has frequent breaks. With DUET, one simply counts the frequency of exertions at various force levels.

In general, HAL and SI are best suited for analyzing short-cycle work tasks with similar force levels throughout the tasks. DUET provides a methodology for assessing tasks with larger variations in force and activity levels as well as inclusion of regular but infrequent activities that may arise throughout the workday. In addition, DUET easily handles evaluation of job rotation schedules by summing CD estimates for each individual task.

Based on data from psychophysical studies, Potvin (2012) developed an equation (also exponential in nature) for localized muscle fatigue to estimate the maximum acceptable effort (MAE), as a percentage of maximum strength, based on the duty cycle of an isolated subtask. More recently, this equation has been used to develop a new method to determine calculation of rest allowances across multiple subtasks to prevent the development of localized muscle fatigue (Gibson & Potvin, 2016). While the fatigue failure model and the MAE model share some interesting similarities (e.g., both are based on exponentially decreasing functions based on a maximal value), it should be noted that the fatigue failure model focuses on damage to tissues more difficult for the body to repair, which are associated with chronic MSDs, while the MAE approach focuses on prevention of physiological muscle fatigue development during work. Both are important issues for improving design of the workplace by the ergonomist, with the latter focusing on muscle fatigue and the former on tissues experiencing more chronic and longer lasting damage.

As with all risk assessment tools, DUET has attendant limitations. It should be noted that DUET was developed for practitioner ease of use and that this required some trade-offs to be made. One trade-off was that we focused on what we consider to be the two most important loading variables contributing to MSDs (stress and number of cycles). However, several other variables are known to influence upper extremity MSD risk. Clearly, factors such as duty cycle, rest/recovery, speed of work, and individual characteristics will influence MSD risk but are not addressed in the current tool. Work is underway to better understand the role of these factors. The use of a perceived exertion scale to estimate force is a drawback, and we hope to develop more quantitative methods for force assessment. In this regard, it should also be noted that if perceived exertion estimates are obtained from the workers themselves, muscle fatigue might alter perceived exertion estimates even when actual forces remain constant (Fontes et al., 2010). Additionally, it is important to note that DUET has not yet been evaluated for its ability to identify incident DUE cases. Further research on the tool is clearly necessary. However, results of the current study demonstrate promise in terms of use of fatigue failure approaches to address these and other issues.

In summary, we present in this paper the Distal Upper Extremity Tool, a new risk assessment tool for DUE disorders predicated on fatigue failure principles. A Web-based version is available at http://DUET.pythonanywhere.com, which also includes a DUET user's manual. This tool is designed to assess the daily dose of exposure to DUE stresses and requires an estimate of force using the OMNI-RES scale and the number of daily repetitions for each DUE task performed during a workday. The tool was validated against an existing epidemiological database and demonstrated strong dose-response associations with five separate DUE outcomes. Results of the validation support the use of fatigue failure techniques in the assessment of DUE MSD risk.

KEY POINTS

- A practitioner-friendly Distal Upper Extremity Tool (DUET) is introduced, based on the premise that upper extremity musculoskeletal disorders (MSDs) are the result of a fatigue failure process.
- DUET has a cumulative damage metric that estimates a daily dose of exposure based on the estimated exertion level and the number of repetitions for each task performed.
- The DUET cumulative damage metric demonstrated a dose-response relationship with five separate DUE outcomes in logistic regression analyses, both unadjusted and adjusted for site, gender, age, and BMI.
- The strong associations observed for the DUET cumulative damage measure and DUE outcomes support the use of fatigue failure methods in assessing MSD risk.

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