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Predicted endurance times during overhead work: influences of duty cycle and tool mass estimated using perceived discomfort

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ABSTRACT

A need for overhead work remains in several industries and such work is an important risk factor for shoulder musculoskeletal problems. In this study, we evaluated the effects of duty cycle and tool mass on endurance times during overhead work. A psychophysical approach was used, via a new methodology that was implemented to more efficiently estimate endurance times (rather than through direct measurements). Participants performed a simulated overhead task in specified combinations of tool mass and duty cycle. Both duty cycle and tool mass have substantial effects on the development of fatigue and estimated endurance times, though the former was more substantial and an interactive effect was evident. Gender differences were not substantial, except when using the largest tool mass. We recommend that, for two-hour periods of overhead work, tool masses greater than 1.25 kg should be avoided, as should duty cycles greater than 50%.

Practitioner Summary: The current results may facilitate enhanced design and evaluation of overhead work tasks. In addition, the new estimation approach that was employed may enhance the efficiency of future studies using a psychophysical approach (ie using extrapolation of patterns of reported discomfort to predict longer term outcomes).

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KEYWORDS
Overhead work; perceived discomfort; fatigue; gender; psychophysics; guideline

1. Introduction

The shoulder is the second most common site (after the lower back) of work-related musculoskeletal disorders among industrial workers (Grieve and Dickerson 2008; Kolstrup 2012; Grobler 2013). Among a variety of risk factors that have been identified, overhead work (also termed over-shoulder work) in particular has been found consistently to be an important risk factor for the development of shoulder disorders (Svendsen et al. 2004; Van Rijn et al. 2010; Mayer, Kraus, and Ochsmann 2012; Dalbøge et al. 2014; Sterud, Johannessen, and Tynes 2014; Hanvold et al. 2015; Linaker and Walker-Bone 2015; Cudlip, Meszaros, and Dickerson 2016). Overhead work also leads to the development of localised muscle fatigue and discomfort (Nussbaum 2001; Kolstrup 2012; Blache et al. 2015), which can compromise task performance in more extreme cases (Sood, Nussbaum, and Hager 2007) and contribute to the development of subacromial impingement syndrome (Chopp-Hurley and Dickerson 2015).

Despite ergonomic improvements in many workplaces to control biomechanical exposures, a number of tasks still require workers to perform overhead work, such as in construction or automotive assembly (Habes, Carlson, and Badger 1985; Van Rijn et al. 2010; Maciukiewicz et al. 2016). In some situations, assistive devices may be effective. For example, Rempel and Barr (2015) reported substantial reductions in physical demands during overhead drilling, by minimising the need for elevated arm postures using custom drilling device. However, some workspaces are restricted in terms of space or the feasibility of using such assistive devices. In such cases, ergonomic guidelines for exposures to overhead work could be of benefit.

However, while there is a growing body of evidence regarding overhead work, it has largely addressed the impacts of different task conditions on biomechanical demands and muscular load (Engin 1980; Herberts et al. 1984; Chopp, Fischer, and Dickerson 2010; Maciukiewicz et al. 2016). Practical guidelines regarding overhead work are, in contrast, relatively limited. In a previous investigation (Nussbaum et al. 2001) duty cycle influenced both endurance and fatigue times, yet arm reach and hand orientation did not have consistent effects. This, and an earlier study (Wiker et al. 1989), indicated that lower duty cycles were more acceptable. In other work, heavier hand tools had a substantial effect on subjective ratings (Garg, Hegmann, and Kapellusch 2006). Previous work has demonstrated

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that overhead work height can affect fatigue, discomfort and task performance (Sood, Nussbaum, and Hager 2007), though other work (Nussbaum et al. 2001) did not find such an effect. The influence of work height may thus be relatively task specific, for example depending on the task demands and work orientation.

Developing guidelines for overhead work presents a number of challenges. Even if focusing only on the shoulder joint, a relatively complex biomechanical/musculoskeletal system is involved which makes it challenging to obtain direct measures or predictions of potentially relevant outcome measures (e.g. levels of muscle recruitment or fatigue). Perhaps for this reason, psychophysical methods have been used commonly in this context. Such methods rely on an individual's ability to identify acceptable working conditions – often as a function of different task parameters and presumably stemming from biomechanical and physiological integration (Potvin et al. 2000; Trask et al. 2008) – and are based on measures or temporal changes in perceptions (e.g. of fatigue or exertion) or voluntary endurance limits. Psychophysical approaches remain appealing for several reasons, including as an accepted job design criterion (Dempsey 1998; Fernandez and Marley 2014; Fischer and Dickerson 2014) with high reliability, particularly during performance of an intermittent overhead task (Sood, Nussbaum, and Hager 2007); associations between subjective and objective measures (Öberg, Sandsjö, and Kadefors 1994; Rempel et al. 2010); and the potential 'protectiveness' of derived limits (Snook, Campanelli, and Hart 1978; Maikala et al. 2014).

An additional challenge, though not specific to overhead work, is the wide range of task conditions (or task parameters) that can be involved. Some earlier work, while providing practical results, assessed only prolonged isometric effort (Garg et al. 2002). However, overhead work in many industries (e.g. automotive assembly and aircraft manufacturing) is more likely to be intermittent. A range of intermittent tasks can be characterised by three parameters, specifically exertion level, duty cycle and cycle time, and these aspects can have relatively complex and potentially interactive effects on fatigue and endurance (e.g. Iridiastadi and Nussbaum 2006; Dickerson et al. 2015).

Other than working height, as summarised above, the present study was completed to address what were considered two additional important task parameters that are relevant to overhead work – duty cycle and tool mass – and to obtain results that could be used for purposes of practical guidelines. Our specific aim was to compile distributions describing the capacity for completing work tasks in several combinations of duty cycle and tool mass without substantial discomfort. A psychophysical approach was used, the potential benefits of which were noted, and which focused on endurance time (ie the duration for which a given task can be completed). However, a common limitation of the psychophysical approach is the long experimental durations typically required. To address this, a preliminary study was completed, the results of which allowed us to develop a relatively efficient procedure to estimate endurance time, rather than using more time-consuming methods to measure these directly. Based on prior evidence (e.g. Winkel 1996; Nussbaum et al. 2001; Moore and Wells 2005; Oliveira, Silva, and Coury 2011; Potvin 2012; Dickerson et al. 2015), we hypothesised that both duty cycle and tool mass influence endurance times during intermittent overhead work.

2. Methods

2.1. Participants

Thirty-six participants (24 males and 12 females) were recruited from the local university and community and completed the experimental procedures. Respective means (SD) of age, stature and body mass were 25.3 (8.7) yrs., 179.0 (6.3) cm, 80.7 (13.3) kg for males, with corresponding values of 25.2 (8.0) yrs., 166.8 (6.2) cm and 61.3 (4.1) kg for females. Participation was limited to individuals who either had recent manual work experience or who did upper extremity exercise on a regular basis. The intent of this selection process was to obtain a participant pool representative of assembly workers, in terms of familiarity with physical work and level of conditioning. Potential participants were also screened for any current or recent injuries or musculoskeletal disorders that might have affected their performance in the experiment. All participants had previous manual work experience, with a mean (median) reported employment duration of 4.0 (2.5) years. After a brief introduction to the experiment, written informed consent was obtained, using procedures approved by the Virginia Tech Institutional Review Board (IRB).

2.2. Experimental design

This study was designed to quantify the effects of duty cycle and tool mass on the ability to complete overhead work tasks. Several objective and subjective measures have been used in similar prior research. Subjective ratings of discomfort were used here, given prior evidence of sensitivity to task conditions generally and both sensitivity and reliability during overhead work (Nussbaum et al. 2001; Garg, Hegmann, and Kapellusch 2006; Sood, Nussbaum, and Hager 2007; Rempel et al. 2010). Three masses and duty cycles were selected based on observations and measurements made at automotive assembly plants, and subsequent analyses of video recordings of several assembly tasks. Specific levels of mass and duty cycle (see Table 1)

Table 1. Treatment combinations of tool mass and duty cycle. Each participant performed a subset of the nine exposures (E1 … E9) as described in the text.

	Tool mass (kg)		
Duty cycle (work duration)	0.5	1.25	2.0
33% (18 s)	E1	E2	E3
50% (27 s)	E4	E5	E6
67% (36 s)	E7	E8	E9

were selected to be representative of the range of levels common in the noted plants. Note that absolute levels of tool mass were used, rather than values normalised to individual or group (e.g. gender) capacity. This approach was used mainly because absolute masses were considered to have more practical relevance, given that loads are not typically adjusted to an individual worker or group (though self-selection and worker assignment do occur). A single cycle time of 54 s. was used, consistent with common values in automotive assembly. Using a within-subjects design, participants were exposed to a subset of the nine combinations of duty cycle and tool mass.

A single simulated overhead task was designed and implemented in the laboratory, similar to that described earlier (Sood, Nussbaum, and Hager 2007). Briefly, participants stood underneath a height-adjustable (up to 263 cm) overhead platform, and an inverted keyboard was attached to the bottom of this platform. Participants used a common (non-functional) electric drill, into which a short wooden dowel was chucked, to tap four designated buttons on the keyboard. Two wires were strung over the keyboard, requiring the participants to move the drill vertically between keys. This approach was used to capture the needs for precise movements to targets and obstacle avoidance, again based on observations of actual assembly tasks and their respective demands. Fixed pacing during the task was achieved using a digital metronome set at 80 beats/min. Participants were instructed that keeping pace with the metronome was more important than the accuracy of hitting the correct keys, but that they should also do their best to hit the correct keys in the correct order. Computer-generated tones ('beeps') were used to indicate the impending and actual start of the working portion of each cycle as well as the end of each portion.

A single overhead working height was used and set relative to individual anthropometry, the same as the middle height ($H2$) used in the noted study by Sood, Nussbaum, and Hager (2007). This height was determined using two measures from the dominant upper extremity: $M1$) hand elevation when the upper arm is held horizontal and the elbow is flexed at 90°; and $M2$) hand elevation with the arm in full extension (overhead reach) with shoulders parallel to ground. Hand elevation was measured to the centre of the grip, while participants held a small cylindrical object. The overhead work task was then performed at an elevation $= M1 + 0.40\ (M1–M2)$.

One practice session was conducted, followed by three experimental sessions in which different task conditions were employed. Two consecutive experimental sessions were always separated by at least 48 h, to minimise residual fatigue from the previous session. To minimise diurnal effects, all sessions were conducted at approximately the same time of day.

2.3. Preliminary work on temporal discomfort patterns

In designing the remainder of the experiment, we employed a novel approach in the interest of efficiency. At one extreme, each participant could have performed the task in each of the nine exposure conditions, to their limit of endurance. Instead, we completed preliminary work that verified earlier results of monotonic and roughly linear increases in perceived shoulder discomfort during intermittent overhead work (Sood, Nussbaum, and Hager 2007). Specifically, we sought to determine cutoff levels, based on this discomfort, to minimise the trial durations to be used in the experiment.

From among the nine exposures (Table 1), participants completed E9 and E5 here. The former condition was chosen as an indicator of an extreme exposure, with the latter considered as moderate. Other 'easier' conditions were not used, since they would provide less data useful towards our goal of verifying patterns of fatigue development over a reasonable task duration. The overhead work task was performed at the noted height and using the procedures summarised earlier. Twelve participants (8 males and 4 females) were involved, and were recruited using the same criteria as for the main experiment. Each participant completed the two conditions (E9 and E5) in a counterbalanced order and on different days separated by at least 48 h. The tapping task was completed, as described above, for two hours or until the individual endurance limit. Ratings of perceived discomfort (RPDs) in the shoulder region were provided using Borg's 10-point scale (Borg 1982), and were obtained after each odd-numbered cycle, or roughly every two minutes.

RPD increases over time were generally monotonic and roughly linear for both exposure conditions (Figure 1). Three exceptions can be seen in the extreme (E9) condition. In one case, a participant exhibited an initial linear increase in RPD, but (perhaps heroically) maintained a high level of discomfort for nearly an hour. In two other cases, a participant reported a consistent level of discomfort (RPD = ~2 and ~3) for a prolonged period followed by a rapid increase. In the former, we suspect that the participants had some difficulty in conceptualising the RPD scale

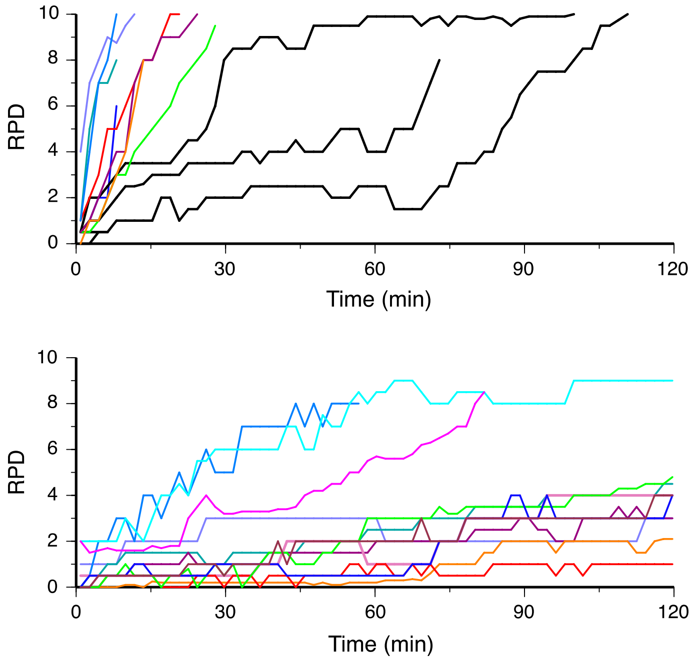

Figure 1. RPD levels over time in the extreme (E9, top) and moderate (E5, bottom) conditions. The majority of RPD curves were roughly linear, with three exceptions indicated by thicker lines in the top figure and discussed in the text.

and applying it to their perceptions. In the latter cases, a linear fit still appears to describe the general temporal trends, but there may still have been difficulty in using the scale (e.g. over-reliance on previous RPD ratings). To overcome such limitations, we added specific practice (calibration) using the RPD scale in the main experiment, as described below. Results from one participant in the E9 condition are not shown, since the experiment was stopped due to substantial pain reported in the biceps.

A qualitative approach was used to analyse these data, the goals of which were twofold. The first was to determine whether there were consistent temporal patterns in RPD to allow us to adequately characterise the progression of fatigue. The general linear behaviour noted above argues for such reliability. The second was to determine a minimum trial duration to be employed in the main experiment, and again we sought to minimise the trial duration to allow for efficient data collection and the possibility of conducting multiple trials in a single session. To achieve this second goal, we determined the minimum trial duration that would allow us to extrapolate results and thereby make predictions of what would occur for a longer trial (here, two hour durations were of interest, as common in automotive manufacturing using job rotation schedules).

Categorisation

We first defined a 'cut-off' value of RPD = 7 (R_C). On the 10-point scale used, this level corresponds to 'Very Strong' perceptions of discomfort, and was posited as a maximal level at which work should be performed so as to not substantially increase risks of injury or performance decrements. Using $R_C = 7$, we formed a 'Categorization Matrix' using different values of time (between 0 and 120 min) and reported RPD levels (Table 2). For given values of time (T) and levels of RPD (R), we determined the proportion of trials that lasted the full two hours with and without reaching R_C. Ideal results would involve all participants and all trials being correctly categorised (in the 'X' cells of Table 2). By iteratively testing different values of T and R, we determined values that maximised the number of trials correctly categorised.

Table 2. An example Categorisation Matrix for determining critical trial durations and RPD levels. The 'X' entries indicate correct categorizations.

		Completed 2 h without reaching R_C?	
		Yes	No
Reported *R* by *T* minutes?	Yes		X
	No	X	

From these procedures, a minimum trial time was determined to be 30 min and the critical RPD level to be 3. An inspection of the RPD data (Figure 1) confirms these values. In other words, 30 min appears to be adequate, since several participants reached high levels of discomfort (RPD = 7) by this time. Or, when high levels of discomfort were not reached by 30 min, the RPD pattern was sufficiently characterised to allow for extrapolation. Use of the categorisation scheme above resulted in only one of the 24 trials being mis-categorised; this was likely due to the noted underestimation of RPD that may have occurred. A critical level of RPD = 3 was concluded for use when substantial fatigue develops sooner than 30 min. In these cases, if RPD reaches 3 quickly it will subsequently continue to increase rapidly. By limiting trials to either 30 min, or an RPD of 3, we concluded that we can minimise the level of imposed discomfort and reduce exposure duration, and thereby be able to conduct multiple trials in a single experimental session.

2.4. Procedures

2.4.1. Practice and familiarisation

In the initial practice session, participants viewed video recordings of selected overhead assembly tasks to provide familiarisation with the real work equivalent of the experimental task simulations. They also practised providing RPDs using Borg's 10-point scale (Borg 1982), which was used in the experiment to obtain ratings of perceived discomfort (RPDs) in the shoulder region. For this practice (or calibration), participants were asked to hold a mass in their non-dominant hand, with their arm abducted to horizontal. The mass was selected so that total shoulder loads were approximately 40–50% of individual capacity, and it was held in a static posture until the limit of endurance. At roughly 5-s intervals, participants provided their RPDs using the 10-point scale, which was visible throughout this and the subsequent experimental sessions. Participants provided their subjective ratings of discomfort as they progressed through the scale (ie from 0 to 10), which required about 1–2 min. By this procedure, we intended for participants to better conceptualise the RPD scale and thereby provide more reliable values.

2.4.2. Selection of treatment conditions

To minimise the number of treatment conditions per participant and the experimental duration on a given day, the entire experiment was divided in two sections that were completed on separate days. Performance in the first section determined the conditions to be tested in the second section. Each participant was exposed to three conditions in the first section, specifically E3, E5 and E7 (the off-diagonal in Table 1). E5 involves the respective middle levels of the two factors, E3 combines the highest tool mass with the lowest duty cycle and E7 has the highest duty cycle and lowest tool mass. Based on the results from the E3, E5 and E7 conditions, predictions are made as to whether participants could perform this task for 2 h without reaching R_C, the 'cut-off' value of RPD = 7. Note that the three conditions were completed in a counterbalanced order, and that each was done for 30 min, or until RPD = 3 was reached, whichever occurred first.

Each participant was then given a Pass (P) or Fail (F) status for each of the initial set of three conditions. A Pass was given if it was predicted that the participant could perform the task for 2 h without reaching R_C, and given a Fail otherwise. Such predictions were done using simple linear regression, by first fitting the RPD data obtained (vs. time) then extrapolating using the linear model (time to reach R_C); a maximum extrapolated time of 120 min was used. Participant's Pass or Fail status on the treatments E3, E5 and E7 then determined the number and type of treatments they performed in the second section of the experiment (Table 3). In addition, all participants performed trials in the E6 and E8 conditions in the second section, to obtain data on these relatively harder treatment combinations. While we assumed that 'passing' a given condition implies passing on an 'easier condition', obviously no such inferences could be made for more difficult conditions. As evident from previous results (Figure 1), E9 could not be performed for 2 h, with the majority of the participants having very short endurance times. Therefore, E9 (the most demanding treatment combination) was excluded from testing in the main experiment.

The approach for deciding on the second set of treatment conditions (Table 3) can be illustrated with the help of the following example. Assume a participant 'passes' conditions E3, E5 and E7. Then according to Table 3, the participant has to perform conditions E6 and E8. The reasoning is that the participant should be able to pass conditions E1, E2 and E4 (Table 4). Passing condition E3 implies that a participant can pass E1 and E2, since both of the latter have the same duty cycle as E1 but a lower tool mass.

Table 3. Number of exposure conditions performed in the second experimental section, based upon the pass/fail status (P/F) obtained from conditions in the first section (E3, E5 and E7).

E3	E5	E7	# of conditions in second section
P	P	P	2 (E6, E8)
P	P	F	2 (E6, E8)
P	F	P	2 (E6, E8)
P	F	F	3 (E4, E6, E8)
F	P	P	2 (E6, E8)
F	P	F	2 (E6, E8)
F	F	P	3 (E2, E6, E8)
F	F	F	5 (E1, E2, E4, E6, E8)

Table 4. Example of decision-making for the second set of experimental conditions. Passing E3, E5 and E7 in the first section, implies passing of E1, E2, and E4. E6 and E8 are thus tested in the second set of conditions.

	Tool mass (kg)		
Duty cycle	0.5	1.25	2.0
33%	E1	↑ E2 ←	E3
54%	↑ E4 ←	E5	E6
67%	E7	E8	

Passing condition E5 implies that a participant can pass E2, E4 and E1, since, respectively, these conditions have lower mass, easier duty cycle and lower mass + easier duty cycle. Passing condition E7 implies that a participant can pass E4 and E1, since they both have the same mass as E7 but an easier duty cycle. Since the participant has 'passed' conditions E1, E2, E3, E4, E5 and E7, we need only test the two 'harder' conditions, E6 and E8. Only two conditions are thus listed in the first row of Table 3 (recall that E9 was not tested).

For each participant, relevant task conditions were identified using the procedures described. Two pilot trials were conducted to evaluate the feasibility of the proposed procedures. Results obtained indicated that no more than three exposure levels should be tested in a single day, since the accumulation of residual discomfort from previous trials would likely affect subsequent results. Thus, each participant performed the task under only two exposure levels on the first day (randomly selected from among E3, E5 and E7), up to three on the second day, and any additional levels on a third day.

2.5. *Statistical analysis*

Exposure conditions were compared based on the percentage passing each condition. For purposes of future application, distributions of estimated endurance times (ET: the time to reach the critical RPD = 7 level) are also described. Estimated endurance times were non-normally distributed, primarily due to the 120 min 'ceiling effect'. Thus, Friedman's non-parametric *F* test was used to assess the effects of duty cycle and tool mass, with gender included as a blocking effect. Factor effects were considered significant when $p < 0.05$, and *post hoc* comparisons were made using Tukey's HSD test.

3. Results

Percentages of participants passing each condition are summarised in Table 5, with these percentages mirroring the 'difficulty' involved in each. Extrapolations of RPD values yielded estimates, for each participant, of when the level of RPD = 7 would have been reached. Selected percentiles of the distributions of these estimated measures are provided in Table 6. To aid interpretation, consider an overhead task using a tool mass = 1.25 kg and a duty cycle = 50%. From Table 6, a design target for the 25th percentile should have a work duration of about one hour (64.0 min). For more detailed estimates of selected percentiles, cumulative distributions of estimated endurance times are provided for the different exposure condition (Figure 2); since all participants passed condition E1 and only one failed E2, no distributions are given for these.

Table 5. Estimated percentage of participants who could 'pass' different conditions involving specific tool masses and duty cycles. Note that passing corresponds to the predicted ability to perform the overhead task for 2 h without reaching RPD = 7.

	Tool mass (kg)		
Duty cycle (%)	0.75	1.25	2.0
33	100.0%	97.1%	80.6%
50	94.4%	80.6%	30.6%
67	25.0%	11.8%	*

*Data not obtained, though the estimated percentage completed will be close to zero based on preliminary results described in the text.

Table 6. Percentiles of estimated endurance times (minutes) for each duty cycle (DC) and tool mass. Note that a maximum time of 120 min was investigated here (ie actual endurance times may exceed this limit in some cases).

		Tool mass (kg)		
	Percentile	0.75	1.25	2.0
DC = 33%	75%	120.0	120.0	120.0
	50%	120.0	120.0	116.6
	25%	120.0	120.0	74.5
DC = 50%	75%	120.0	120.0	101.7
	50%	120.0	92.8	43.4
	25%	120.0	64.0	17.2
DC = 67%	75%	74.0	22.9	
	50%	27.5	12.3	*
	25%	10.7	6.7	

*Data not obtained, though endurance times are likely to be relatively short based on preliminary results described in the text.

Predicted ETs overall did not differ significantly between genders ($p = 0.36$), with females and males having overall mean (SD) endurance times of 77.8 (46.5) and 81.6 (56.0) minutes, respectively. There was a significant gender x mass interaction effect ($p = 0.04$); both genders had similar endurance times using the two lighter tools, though males had ~20% greater values with the 2.0 kg tool. There were significant effects of duty cycle ($p < 0.0001$), tool mass ($p < 0.0001$), and their interaction ($p = 0.0005$) on estimated ETs (Figure 3). Overall, ET was shorter with a higher duty cycle and tool mass, with the effect of tool mass being somewhat larger for the higher duty cycles (and vice versa).

4. Discussion

This study was performed with a primary aim of determining the influences of duty cycle and tool mass on endurance time during intermittent overhead work. Given the extensive time required to directly measure endurance time in multiple tasks conditions, a new procedure was developed from which these times were estimated. In this approach, the progress of reported discomfort was used, which thereby minimised experimental and participant time demands. Specifically, the estimated endurance times in the tested conditions (E1–E8) suggest the total duration that would have been required if each participant

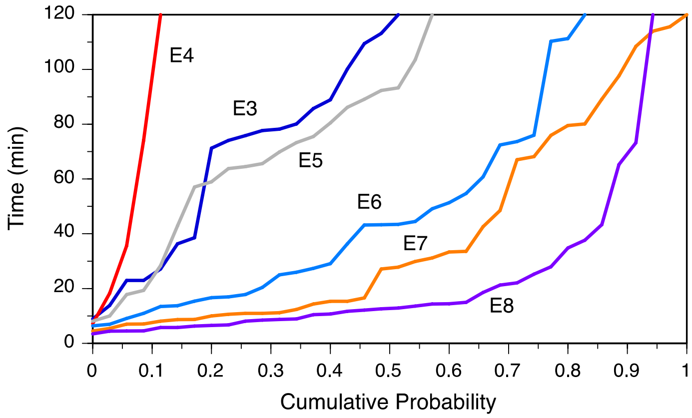

Figure 2. Cumulative distributions of estimated endurance times (estimated time to reach RPD = 7) for each exposure condition (see Table 1).

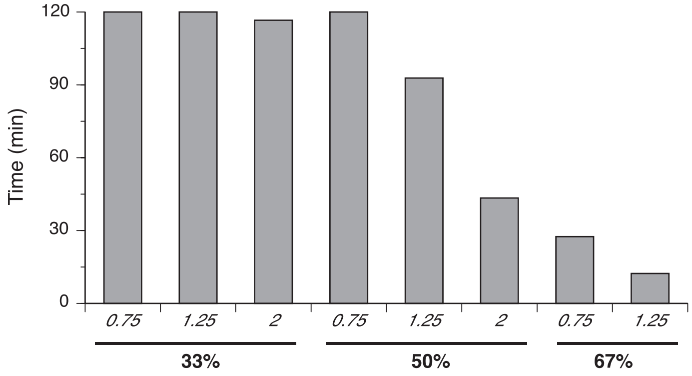

Figure 3. Median estimated endurance times for each duty cycle (in bold at bottom) and tool mass (kg, in italics). Note that a maximum time of 120 min was investigated here (ie actual endurance times may exceed this limit in some cases).

completed all conditions (to an RPD = 7). This yields a mean of ~640 min. In the current procedure, though, each participant completed a subset of conditions (a mean (SD) of 5.1 (1.0) conditions), and each continued only for 30 min or until RPD = 3. Across all participants, the mean (SD) duration was 103.4 (25.9), or an overall time saving of nearly 85%. With respect to the task factors investigated, duty cycle was found to be more influential than tool mass in terms of the development of discomfort and estimated endurance times, at least over the range of levels investigated. Gender overall was not associated with significant or substantial differences in endurance times, though males did have ~20% longer times using the heaviest tool.

Increasing duty cycle led to substantial reductions in the percentage of participants who could complete the simulated task for 2 h (Table 5) and estimated endurance time (Table 6). Similar, and apparently non-linear, effects of increasing duty cycle, were reported earlier by Potvin (2012) who compiled several earlier studies to develop an equation that predicts maximum acceptable loads for repetitive tasks based on duty cycle. The current results, in terms of the effect of duty cycle, are also consistent with earlier studies that involved work including arm elevation (Wiker et al. 1989; Nussbaum 2001; Nussbaum et al. 2001; Garg, Hegmann, and Kapellusch 2006). An increase in perceived discomfort and a decreased endurance time with higher duty cycle are likely primarily a result of the more prolonged effort and lack of adequate rest between cycles of work. Tool mass was also found to reduce endurance times, consistent with earlier reports during load-handling activities with arm elevation (Oliveira, Silva, and Coury 2011; Blache et al. 2015) and estimates of muscle activity (Dickerson, Chaffin, and Hughes 2007). The influence of tool mass, via increased muscular effort, is also consistent with a study that examined prolonged static efforts involving arm elevation (Garg et al. 2002), and the non-linear effect of exertion level on endurance times (e.g. Rohmert 1973; Frey Law and Avin 2010).

Tool mass and duty cycles were assessed here in several combinations and demonstrated interactive effects. Specifically, the influence of increasing tool mass appeared more substantial with a higher duty cycle, and equivalently the influence of a higher duty cycle was more evident with increasing tool mass (Figure 3). There thus appears to be a compounding (non-additive) effect of duty cycle and muscular effect, and which probably related to the noted non-linear relationship between muscle effect and endurance time. Among the combinations of tool mass and cycle time examined here, several appear 'acceptable' based on long estimated endurance times. Specifically, tool masses up to 0.75 kg with duty cycles less than 50%, and tool masses up to 1.25 kg with duty cycles less than 33%. For larger tool masses, the current results suggest that endurance times will be relatively short.

Substantial differences between genders were not found here, except when using the largest tool mass (2 kg). Earlier work has noted gender differences in muscle fibre distribution, which is associated with an increase in endurance time but a decrease in motor variability and strength capacity (Hägg and Suurküla 1991; Côté 2012; Srinivasan and Mathiassen 2012). Kirk and Sadoyama (1973) investigated the effects of weight and static arm flexion on maximum endurance time. Perceived discomfort and endurance times were similar between genders, regardless of weight held or arm posture assumed. Here, endurance times were also similar between genders when the overhead task was performed with the lighter hand tools (0.75 and 1.25 kg). With the heaviest tool (2.0 kg), in contrast, estimated endurance times were larger for males. In an analogous earlier study of intermittent overhead work, females demonstrated longer endurance times, delayed reports of discomfort, and slower declines in strength (Nussbaum et al. 2001). However, that study used a substantially light 'tool' (0.36 kg), and a slightly different task that may have involved distinct patterns of muscle recruitment. In the Sood, Nussbaum, and Hager (2007) study, which used the same task as the present one, no differences were found in the timing of RPD increases between genders using a 1.25 kg tool (the middle level used here).

Thus, gender differences seem to be dependent on external load (tool mass). The evidence related specifically to overhead work, summarised above, suggests the following: females have longer endurance times with low external loads (lesser tool mass), shorter endurance times with higher loads, and comparable levels in between. As reviewed elsewhere (e.g. Nussbaum et al. 2001; Côté 2012; Hunter 2014) there are a number of potentially contributing factors to gender-related differences in fatigue development, including differences in muscle fibre distribution noted earlier. In addition, females have typically lower strength, especially in the shoulder musculature, but also lighter body segments and segmental centres-of-mass located closer to proximal joint centres. We speculate that these latter differences in strength and anthropometry essentially 'cancel out', and that the difference in fibre distribution, along with the exertion-effort relationship, may explain the particular pattern with respect to external load described above. More specifically, with low levels of external load the influence of gender differences in fibre type may predominate, leading to longer endurance times among females. With increasing loads, absolute levels of muscle force would increase for both genders. Yet, the relative effort among females would be higher, given a lower level of strength, leading to shorter endurance times. Based on earlier work (Nussbaum et al. 2001), conditions here using the 1.25 kg tool likely required levels of shoulder muscle activity on the order of 15–20% of capacity. As such, substantial decreases in endurance time can be expected with the heavier tool, consistent with the large negative slope in the endurance-effort relationship at this level of activity. In other words, females, working at a higher relative effort with the heavier tool, moved further 'down' this relationship than males. As neither muscle activity nor strength was measured in the present study, however, such speculations require further investigation.

A clear potential limitation in this work was the reliance on predicted vs. directly measured endurance times. While this approach yields experimental efficiencies, it relies strongly on the assumption of a linear temporal progression of perceived discomfort. Our initial results support this assumption (Figure 1), and we believe the calibration procedure implemented subsequently may have helped to limit some exceptions noted. This assumption is also supported by earlier reports of linear (or nearly linear) increases in perceived discomfort over time for several intermittent exercises, including isometric and isokinetic shoulder activities (Iridiastadi and Nussbaum 2006; Yassierli and Nussbaum 2007; Raina and Dickerson 2009), isometric elbow extension (Yung, Mathiassen, and Wells 2012), isometric handgrip (Byström and Fransson-Hall 1994) and isokinetic torso extensions (Yassierli and Nussbaum 2009). Nonetheless, future work is needed to validate this assumption, for example by specific comparison of predicted and actual endurance times.

There are some additional limitations to the current study that should be considered. First, the experimental task was performed at a consistent (normalised) height and did not simulate any particular occupational activity. Thus, it is unclear whether or to what extent the results will generalise to actual occupational scenarios, particularly given that muscle recruitment can be sensitive to the particular tasks demands (Hunter 2009; Cudlip, Meszaros, and Dickerson 2016) and, as a specific example, endurance times differ with working height (Anton et al. 2001; Nussbaum et al. 2001; Sood, Nussbaum, and Hager 2007) and cycle time (Dickerson et al. 2015). Second, some important exposures that are common during actual drilling tasks were not simulated here, including tool vibration and any torque-reactions; it is unclear whether and to what extent these will influence estimated endurance times. Third, though participation in the study limited to individuals who were considered reasonably representative of actual industrial workers, none had specific expertise with the type of task simulated here. Assuming some level of work conditioning and skill development occurs with prolonged overhead work, the current results may thus be conservative and perhaps best representative of novice workers.

In summary, we developed and applied a new procedure to obtain estimated endurance times using a psychophysical approach, and extrapolation from relatively brief experimental trials. Consistent with earlier evidence, both tool and mass and duty cycle were found to be influential on endurance. However, the latter had a larger effect over the range of factor levels tested, and there was an important interactive effect of these factors. As a general guideline, the results indicate that for two-hour shifts requiring overhead work, tool masses greater than 1.25 kg should be avoided, as should duty cycles greater than 50%. The new procedure described here may be useful for efficient estimation of endurance limits in a variety of tasks.

Disclaimer

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