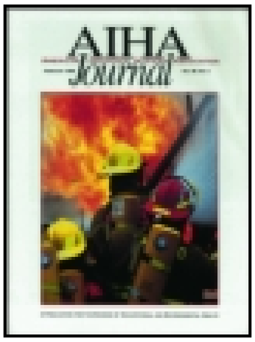

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Fatigue and Endurance Limits During Intermittent Overhead Work

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Shoulder problems are prevalent in industrial work, particularly when tasks require the hands to be used at or above shoulder level. Although extensive research has been conducted on prolonged static exertions, and several guidelines for such efforts exist, there is insufficient information for ergonomic evaluation of tasks that are intermittent and/or dynamic. A laboratory simulation was conducted of overhead assembly work that was both intermittent and dynamic, and which varied the duty cycle (work/rest ratio), arm reach, and hand orientation of a tapping task. Results consisted of endurance times and also the times of fatigue onset as indicated by perceived discomfort and declines in muscle strength. Females exhibited longer (22%) endurance times, delayed reports of discomfort, and slower declines in strength. Significant influences of duty cycle were found on both endurance and fatigue times, yet arm reach and hand orientation did not have consistent effects. Distributions of endurance and fatigue times are presented as criteria for preliminary evaluation of overhead work. Endurance times could be predicted with only moderate accuracy from earlier indicators of fatigue onset. Existing guidelines, albeit developed for static tasks, appeared unsuitable for the simulated overhead assembly efforts examined. Furthermore, such guidelines may fail to capture the substantial interindividual variability observed in this experiment.

Keywords: endurance, fatigue, gender differences, intermittent work, overhead work, perceived discomfort

The problem of shoulder illness in industry has been highlighted by several researchers in the past quarter century,[1–3] and there is some evidence that the prevalence may be rising.[4] In the United States the reported number and incidence rate of shoulder soft tissue injuries were third only to those of the legs and back.[5] Mechanization of industrial work processes has resulted in simplified and less strenuous movements,[6] yet the use of the arms and required rates of motion have increased.[7,8] Modern work tasks may demand less effort and energy, but the stereotypic repetition can impose local stress on the musculoskeletal system.

Several risk factors that may contribute to shoulder musculoskeletal disorders (MSDs) have been identified, and include static loads, lack of sufficient rest, and nonneutral postures. In particular, working at or above head level has frequently been cited on the basis of epidemiological, physiological, and biomechanical studies.[9–11] Nearly 70% of occupational health clinical patients with shoulder pain stated they had worked with their hands at or above shoulder level.[12] A later study found an odds ratio of 11 for rotator cuff tendonitis in two occupational groups working at shoulder level.[13] Hagberg[14] proposed that working with elevated arms may accelerate degeneration of the rotator cuff tendons through impairment of circulation due to static tension and compression of tendons against underlying bone. Work tasks that require continuous arm movements can generate load patterns with substantial static components.[15]

The prevalence and costs of MSDs lead to a need for control measures. Administrative controls, such as prescribed work/rest cycles, are attractive because they avoid substantial redesign of tasks. These same controls, however, are difficult to implement because there is a general lack of task-specific dose-response relationships available, in particular for shoulder MSDs. This lack stems, in part, from the multicausal nature of cumulative-type trauma and unknown interactions among risk factors. There also appears to be no obvious consensus on how different

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risk factors can or should be pooled and interpreted as a dose.[15,16]

The following work is based on the assumption that localized muscle fatigue can be used as an indicator of injury risk, and that by minimizing fatigue, risk will also be reduced. Specific pathophysiological relationships between fatigue and injury are not well defined. Some authors, however, have implicated muscle fatigue as a causative factor in work-related chronic muscle pain.[17] Mechanisms proposed for the causal relationship are diverse, including the relative avascularity of rotator cuff tendons,[9] elevated intramuscular pressure,[18,19] impaired circulation,[20–22] friction,[14] ultrastructural ruptures,[23] increased passive tissue demands,[24] and several biochemical effects.[25,26] A number of exposure-effect models, consisting of exposure to certain task parameters and responses with varying degrees of acute and chronic effects, also support this assumption.[15,25,27,28] In addition to its potential role in musculoskeletal trauma, fatigue has well-documented adverse impacts on comfort and performance.[29–32]

Fatigue can be measured using a variety of subjective and objective tools. Among the most common approaches, considered by some a gold standard,[33] is assessment of decreases in muscle contractile capability elicited either through maximum voluntary exertions or external stimulation. Electromyography (EMG) is another common approach, and can often detect physiological changes before deterioration of mechanical performance. Fatigue-related changes in the myoelectric power and spectrum are well documented. EMG signals, however, are highly sensitive to influences other than fatigue,[34] and the classic changes associated with fatigue have not been consistently observed during dynamic or intermittent exercise.[35–38] Subjective measures are often used to supplement physiological measurements. Perceived exertion or discomfort is thought to be influenced by local muscle or joint strain[8,39] and the local build-up of metabolites. Although subjective ratings are easy to administer, they may reflect more than the underlying process (i.e., fatigue), and large individual differences have been observed.[40]

Extensive studies have been conducted on fatigue during static exertions. The early work of Rohmert,[41,42] describing endurance as a function of exertion level, epitomizes several later studies. Despite the implications of Rohmert's illustrations, more recent evidence indicates that even minimal loads, on the order of 5–15% of individual capacity, cannot be sustained past an hour without rest.[43–45] A recent review suggested that the static load-endurance relationship can vary substantially depending on the muscle group and type of task.[46]

Relatively little work has been done on capacity during intermittent work or tasks with work/rest cycles, although endurance time is known to be enhanced over sustained static contractions.[36] In one such study of repeated short cycle elbow flexions,[47] static endurance limits of 8% of maximum and a mean of 14% for intermittent static contracts were reported. In similar rapidly cycling tasks,[48] intermittent handgrip contractions at a mean intensity of 17% of maximum were found acceptable. During intermittent static arm pulling, with 10 sec of work interrupted by 5 sec of rest, myoelectric changes were observed within 3 hours at a contraction level of 14% of maximum, whereas a 10% level was maintained up to 7 hours.[45] Two reformulations and extensions of Rohmert's early work on endurance times for static exertions with rest breaks have also been presented.[49,50]

Few studies have been conducted to investigate fatigue during dynamic exercise, one reason being the practical difficulty that many of the capacity measures recover rapidly.[26,51,52] Two particular studies[53,54] avoided much of this difficulty by allowing experimental participants to self-select cycle duration within a repetitive task, and treating the resulting cycle durations as a measure of fatigue accumulation. These studies, which involved vertical movements of a small tool in front of the body, demonstrated substantial effects of rate and force of movements on work duration. In addition, the self-selected cycle durations exhibited clear inverse relationships with relative effort levels. Results such as these suggest that subjective (psychophysical) approaches may allow for reliable task assessments. Yet, given the number of alternate methods to measure fatigue, and the potential limitations of subjective ratings, there has been little investigation of relationships within and among these methods. If such relationships exist, it may be possible to employ simple (e.g., subjective) measures in lieu of more complex or laboratory-based approaches.

In the study presented here, an overhead work task was performed that, based on initial results, required approximately 15–25% of maximum shoulder strength. If existing reports were used to estimate endurance times for this task, widely varying times would be obtained, ranging from 5 min to infinity. Motivation for the study stems from this lack of consistency in available data, and hence justifiable design guidelines, and has a goal of helping to reduce the impact of elevated arm work on shoulder MSDs. Despite extensive results in the literature, none could be found to allow for quantitative design and analysis of overhead work tasks that are both dynamic and intermittent. Data were obtained from laboratory tasks that simulated overhead assembly work, and consisted of maximum endurance times and estimated fatigue onset times based on subjective assessment and decrements in strength. Results were compiled in a form that can provide guidance for ergonomic task design or evaluation. In addition, interrelationships within and between the several dependent measures were examined.

METHODS

Participants

Sixteen participants (8 female, 8 male) were recruited through the use of an advertisement and compensated for their time. Each participant completed an informed consent procedure approved by the Virginia Tech IRB. All participants were right-handed, between ages 18 and 22, and reported moderate levels of physical activity with no recent history of musculoskeletal injuries. Descriptive data are provided in Table I. Each participant attended one training session and eight subsequent experimental sessions. A minimum of 48 hours was required between sessions to control for residual fatigue.

Experimental Tasks

The experiment simulated manufacturing tasks that require overhead assembly (Figure 1). Point-to-point tapping motions between two overhead targets were performed while standing using a 0.36-kg wandlike tool with a 3-cm ball attached at the end. Participants held the wands in their right hands and were instructed to alternately strike the centers of 3.3-cm diameter circular targets that were aligned horizontally and separated by 50 cm (roughly equal to average shoulder span). A computer-generated tone sounded at intervals of 0.75 sec to create a fixed tapping rate. The combination of target size, separation, and tapping interval were chosen through pilot work to comply with standard

TABLE I. Participant Anthropometric Data and Target Heights

	Stature (cm)	Body Mass (kg)	Shoulder Height (cm)[A]	Arm Reach (cm)[B]	Target Height: 50% (cm)	Target Height: 75% (cm)
Mean	171.6	69.4	144.8	211.1	187.7	204.3
Std. Dev.	9.7	12.0	8.9	16.9	12.4	14.5
Range	(158.5–187.5)	(50.0–89.0)	(133.5–159.0)	(190.0–253.5)	(172.5–216.3)	(186.3–240.0)

[A]Measured from the floor to superior aspect of acromion.
[B]Measured from the floor to the center of a thin handheld rod with the arm fully extended overhead.

times estimated from the MTM-1 Predetermined Time System[55] and allow subjects initially to perform the task within the target tolerance.

A 1-min cycle was the primary unit of activity during the experiment. Within each cycle, the tapping task was conducted for fixed durations of work and rest. Participants also performed maximum voluntary exertions (MVEs) and gave ratings of perceived discomfort/exertion (RPEs) at the start of the experiment and at intervals throughout. Blocks of 10 cycles (10 min) of work and rest were repeated until one of the following stopping criteria occurred: (1) shoulder MVE values dropped below 75% of baseline; (2) shoulder RPE increased above 7 (on a 10-point scale); (3) the participant indicated he or she could no longer continue; or (4) 18 ten-cycle blocks (3 hours) were completed. The first three criteria were selected to minimize injury risk, whereas the latter was based on the prevalence of work rotation schedules and an assumption that short-cycle overhead work would rarely be performed for more than 3 hours continuously. In nearly all cases the experiment was terminated on the basis of the third or fourth criteria.

Dependent Measures

MVEs were performed for four shoulder muscles: middle deltoid (MD), trapezius (TRAP), anterior deltoid (AD), and infraspinatus

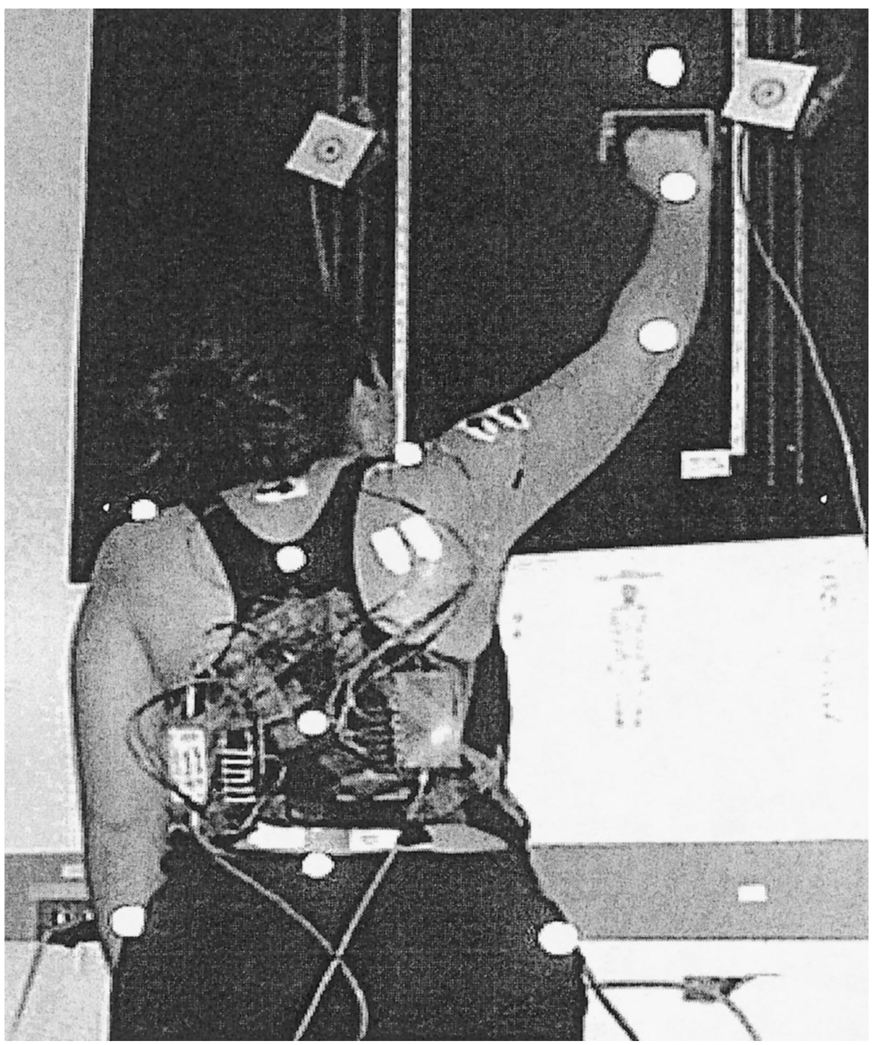

FIGURE 1. Illustration of experimental task during a 75% arm reach and hand pronated condition

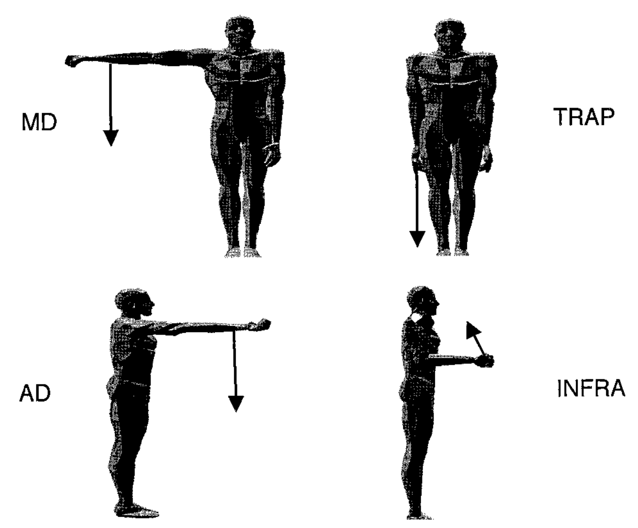

FIGURE 2. Postures used to obtain MVE measures (external rotation of the shoulder was used to test INFRA strength)

(INFRA). These muscles were selected based on prior evidence of their use and fatigability during overhead work,[37,56–61] their prominence and accessibility, and the ability to nearly isolate their function during strength testing. Participants performed MVEs in consistent postures (Figure 2), aided by a fixture built for this purpose. Care was taken to ensure that postural variations were minimized while participants pulled on a handle (TRAP and INFRA), or against a strap placed over their forearm (MD and AD). All MVEs were performed as ramp-up, hold, and ramp-down efforts requiring approximately 5 sec.[62] Practice in the procedures was provided during the initial training session, and verbal encouragement was provided periodically throughout all experimental sessions. Forces were obtained with load cells, sampled and low pass filtered (10 Hz cutoff), and peak values recorded for the respective muscles. All four MVEs, obtained every 10 min, were typically completed in less than 45 sec and were the only interruption to the normal timing of work/rest cycles.

Subjective RPEs were obtained using Borg's CR-10 scale.[63] Care was taken to explain the meaning of the scale values and the need to provide current ratings independently of those previous. After a brief warm-up session, RPEs were obtained globally (whole body) and locally (shoulder and low back). If these values were not zero, the reason was determined, and in some cases subjects returned on a subsequent day. RPEs were also obtained every 5 min during the experiment for perceived discomfort localized to the shoulder.

Electromyographic (EMG) measures were obtained from the four shoulder muscles during MVEs and during the tapping tasks. Pairs of disposable electrodes, spaced 2.5 cm apart, were placed over the bellies of the muscles and parallel to their fiber directions. Placements were marked and measured relative to bony landmarks to ensure consistent placement between days. Raw signals were preamplified near the electrode sites, then rms converted (110 msec time constant) and bandpass filtered in hardware. These processed (rms) signals were sampled at 100 Hz, then low pass filtered (10 Hz cutoff) in software. Ten-second samples of rms-EMG from the end of the first tapping cycle were averaged and normalized to peak values obtained from the first MVE. Assuming a linear relationship between force and EMG, which was verified on a subset of the data, these normalized values were used to estimate the percentage of maximum muscle effort used by each muscle in each condition.

Independent Measures

Variables manipulated in the experiment were arm reach (via target height), duty cycle, and hand orientation. These variables, and their levels, were selected to represent a range of common overhead assembly tasks and to address aspects of task variability that were likely to influence shoulder fatigue. Each variable had two levels, and each participant completed the eight factorial combinations. A double Latin square design was used to minimize order effects and to balance conditions across genders.

Arm reach was either 50 or 75% of a participant's overhead reach capacity (Table I). Arm reaches were measured as proportions of the vertical distance from the estimated shoulder center (5 cm below the acromion) to the overhead grip location, and set by the vertical locations of the targets. The two levels of arm reach were intended to reflect the varying postures associated with different anthropometric and workstation dimensions. The portion of each minute cycle during which subjects were tapping was either 20 or 40 sec, yielding duty cycles (work/rest) of 20/40 and 40/20. Duty cycle was intended to reflect differences in the nature and extent of work tasks typical in light assembly. The tapping task was performed with the hand either pronated (palm facing targets) or supinated, representing extremes in hand/arm orientation. Pronation is similar to what is used in placing or adjusting an object overhead, whereas supination is commonly used while holding an object or tool.

Analysis

Dependent measures obtained during the experiment were MVEs, RPEs, and the time at which the experiment was terminated (T_{END}). As fatigue is commonly defined as a decline in maximum capability, it was expected that MVEs in at least one shoulder muscle would decrease during the course of the experiment. Similarly, shoulder RPEs were expected to increase as localized shoulder fatigue developed. The endurance limit (T_{END}) was simply recorded for each subject and condition, and the time at which RPEs reached 1 (T_{RPE}) was recorded as an indicator of the onset of subjective shoulder discomfort.

Temporal changes in normalized MVE values (with respect to initial values) were analyzed, rather than the magnitudes of these values, to facilitate comparison across conditions and participants. Because there is no accepted standard for deciding, on the basis of a decline in strength, when fatigue has occurred or when it is substantial, an operational measure of the time of fatigue onset was defined. The variability (σ) in a set of MVEs (for a given subject, condition, and muscle) was quantified as the rms error from linear regression ($\sqrt{MSE}$). It was assumed that when the MVE changed by more than $\sigma/2$ (Figure 3), fatigue in that muscle was substantial, and the time was recorded. Initial analysis showed significant differences in σ between subjects and muscles, but not between experimental conditions ($P > 0.1$). Thus, subject-specific values of σ were obtained for each muscle by averaging across conditions. Using the slope of the regression line and the $\sigma/2$ criterion, the time of fatigue onset was obtained as $(\sigma/2)$/slope. These onset times (T_{MVE}) occasionally exceeded 3 hours (the maximum duration), and in some samples MVEs slightly increased. In both cases, the time was set to 3 hours. Student's t-tests were used to determine if the MVEs exhibited a significant ($P < 0.1$) linear change.

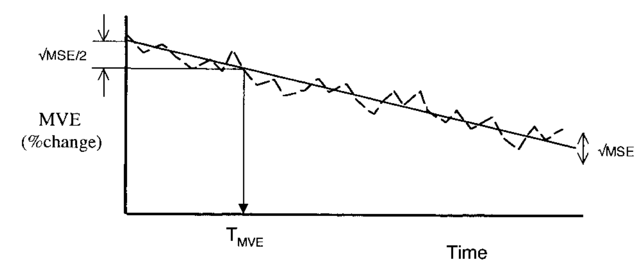

FIGURE 3. Methods used to operationalize time of fatigue onset (T_{MVE}) based on changes in MVE measures

The experiment was analyzed as a repeated measures design, and effects were considered significant when $P < 0.1$. Preliminary analysis of variance (ANOVA) determined whether there were order effects (due to serial presentation of the conditions) or differences between genders, and standard ANOVA to determine the effects of the task variables. Several of the dependent measures were found to be non-normally distributed, particularly due to the ceiling limit of 3 hours. In these cases, nonparametric tests were used, first to determine whether there were differences among the eight experimental conditions (Kruskal-Wallis), and subsequently to examine the effects of the three task variables and their two-way interactions (analysis of variance by ranks).

RESULTS

Order Effects, Gender Effects, and Muscle Use

From ANOVA of the Latin square design, order as a main effect was not found to be significant for T_{END} ($P = 0.9$). The order effect approached significance for T_{RPE} ($P = 0.13$); there was a slight trend toward increasing T_{RPE}, with the latter four conditions averaging 10 min higher than the initial four. Order effects on initial MVE magnitudes were significant for the TRAP ($P = 0.03$), approached significance for the MD ($P = 0.14$), and were not significant for the other two muscles ($P > 0.25$). For all four muscles, there was a trend of higher MVEs in later conditions, but the magnitude of this trend (last vs. first condition) was generally less than 10%. No significant order effects were found for T_{MVE} ($P > 0.2$), although there was a small tendency for T_{MVE} to be 5–10 min longer in later conditions.

Significant differences were found between males and females for T_{END} ($P = 0.002$) and T_{RPE} ($P = 0.002$). More females than males were able to perform the tasks until the 3-hour cutoff (55 vs. 33%). Females also performed the tasks longer than males on average (143 vs. 118 min), and reported discomfort later (74 vs. 65 min). Significant gender differences were also found for T_{MVE}s of the AD ($P = 0.03$) and INFRA ($P = 0.008$), with female values higher by 40 and 30 min, respectively. Although not significant for the remaining two muscles ($P > 0.25$), T_{MVE}s were 14 and 32 min higher for the MD and TRAP, respectively. When these data were analyzed in terms of within-subject ranks, significant Gender × Condition interactions were found for T_{END} ($P = 0.065$) and T_{MVE}s of all muscles except the MD. These interactions indicate a differential response between genders to the eight task conditions, although the magnitudes of gender-related differences were not consistent across the dependent measures. Neither order nor gender effects were significant with respect to activity levels in the four shoulder muscles. Because of the lack of consistency in the magnitudes of gender effects, and the lack of gender-related differences in muscle activity, gender was ignored in all subsequent analyses.

TABLE II. MVE Changes Versus Time (% change/min)

	MD	TRAP	AD	INFRA
Mean	−0.13	−0.08	−0.11	−0.03
Median	−0.07	−0.05	−0.06	−0.02
−/0/+[A]	65/27/8	47/48/5	57/36/7	35/50/15

[A]Percentage showing significant negative changes (−), nonsignificant changes (0), or significant positive (+) changes.

The tasks overall required slightly more activity in the deltoid muscle compared to the other two muscles. Mean (SD) activity levels, reported as a percentage of maximum for each muscle, were found to be 19.1% (7.9) for the MD, 16.0% (6.9) for the TRAP, 19.6% (9.4) for the AD, and 16.9% (7.5) for the INFRA. These activity levels varied with several of the task conditions, indicating different muscle loading patterns. At the lower and higher tapping heights, average MD loads were 22 versus 16% ($P < 0.0001$), and average TRAP loads were 15 and 17% ($P = 0.08$), respectively. The TRAP loads were higher ($P = 0.06$) when the hand was supinated than pronated (17 vs. 15%). Duty cycle had significant effects ($P < 0.02$) on the loads in all muscles except the TRAP ($P = 0.2$). For all muscles, however, the 40/20 duty cycle was associated with levels of muscle activity only 2–4% higher than the 20/40 duty cycle. Because EMG was recorded at the end of each work cycle, the higher activity found in the 40/20 tasks was likely a result of larger fatigue-related increases in amplitude.

Endurance Limit (T_{END})

Experimental condition as a main effect was associated with significant ($P < 0.0001$) differences in T_{END}. Conditions in which the duty cycle consisted of 20 sec of work (20/40) lasted the full 180 cycles of testing in 67% of the trials, whereas the 40/20 duty cycle was completed in only 22% of the trials. This duty cycle effect was significant ($P < 0.0001$), with average T_{END} values of 99.5 and 161.3 min for the 20/40 and 40/20 combinations, respectively. Neither the arm reach nor hand orientation effects were significant ($P > 0.76$), and no obvious trends could be discerned. Significant ($P = 0.082$) interactions of duty cycle with both arm reach and hand orientation were found, but the magnitudes of both interactive effects were small (<10 min).

Fatigue Based on RPE (T_{RPE})

Experimental condition as a main effect was associated with significant ($P < 0.0001$) differences in T_{RPE}. Duty cycle ($P < 0.0001$) and arm reach ($P = 0.039$) both had significant main effects. T_{RPE} was lower in the more strenuous (40/20) duty cycle (24 vs. 100 min), during the 75% reach condition (57 vs. 67 min). The Arm Reach × Hand Orientation interaction was also significant ($P = 0.027$), and was seen as a moderately larger influence of hand orientation during the 50% reach condition.

Fatigue Based on MVE (T_{MVE})

Most experimental conditions yielded decreasing MVEs for all muscles (Table II), with rates of decline of 0.03–0.13 %/min (2–8%/hour). For the MD and AD, most of these decreases in MVE were significant, whereas for the TRAP and INFRA, the majority were nonsignificant. A small number of conditions resulted in significant increases in MVE.

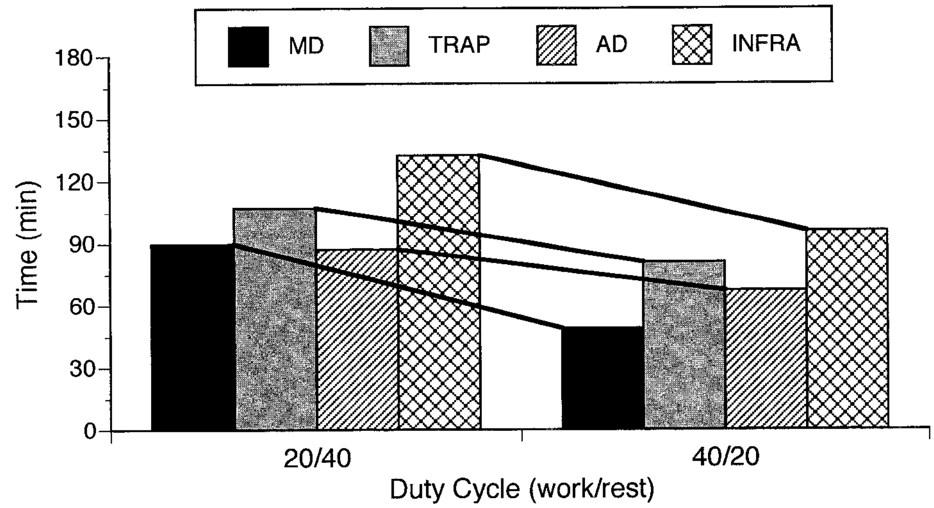

FIGURE 4. Effect of duty cycle on T_{MVE}

Experimental condition as a main effect on T_{MVE} was significant for all four muscles ($P < 0.099$). T_{MVE} was highly variable among conditions and muscles. The two portions of the deltoid were typically the first to show signs of fatigue (based on T_{MVE}), followed by the TRAP, and the INFRA substantially later. Significant differences in T_{MVE} were found between the two duty cycles ($P < 0.014$), an effect that was relatively consistent for the four muscles (Figure 4), with T_{MVE} occurring between 23 and 45% sooner in the 40/20 duty cycle. T_{MVE} was significantly ($P = 0.068$) lower for the MD in the 50% versus 75% reach conditions (65 versus 74 min). The interaction of arm reach with duty cycle was significant ($P < 0.001$) for the MD and TRAP, and approached significance for the AD ($P = 0.13$). For all three muscles, the effect of duty cycle was relatively larger in the 50% reach condition. Signs of fatigue appeared earlier ($P = 0.024$) in the INFRA when the hand was supinated versus pronated (107 vs. 122 min). Hand orientation also had a significant interaction effect with duty cycle ($P = 0.026$), with the orientation effect being restricted primarily to the 40/20 duty cycle.

The four values of T_{MVE} obtained for each experimental condition differed considerably when compared within subjects ($r = 0.28$–0.50). When T_{MVE}s were averaged across subjects, however, the values for each muscle were more consistent ($r = 0.38$–0.90). Across all conditions and subjects, the MD (44%) and AD (25%) most frequently had the smallest T_{MVE}, followed by the TRAP (20%) and INFRA (11%).

Data Interrelations

Correspondences among the several measures of endurance and fatigue times were examined, as was the ability to predict T_{END}. Results describing simple correlations among the measures are given both for the subject-specific data (16 subjects × 8 conditions) and the subject-averaged data (8 conditions). The subject-specific data (Table III) reveals relatively low correlations among the several measures. When examined across subjects (Table IV), however, the same correlations were substantially larger. Descriptive measures of the distribution of endurance and fatigue times were obtained for T_{END}, T_{RPE}, and the smallest T_{MVE} (Table V). In the less demanding duty cycle (20/40), the time onset of fatigue as indicated by RPE or MVE was on the order of 25–50% of the endurance limit. In contrast, the time of fatigue onset was proportionally sooner during the 40/20 duty cycle, and on the order of 10–20% of the endurance limit. The order of fatigue onset as indicated by the two measures (T_{RPE} vs. minimum T_{MVE}) was reversed between the two duty cycles (Table V).

Models were developed for predicting subject-specific T_{END} from T_{RPE} and T_{MVE}. One-by-one comparisons showed consistent nonlinear relationships, and best fits were obtained from logarithmic (ln) transforms of T_{RPE} and T_{MVE}. Using just T_{RPE}, T_{END} could be moderately predicted, with r^2–adj = 0.52 and a standard error of 36.3 min [$T_{END} = 26.1 + 30.3 \ln(T_{RPE})$]. This prediction was biased, though, in that T_{END} was overestimated when less than 120 min, and slightly underestimated otherwise. In addition, the large number of trials that reached the 180-min cutoff were, in

TABLE III. Correlation Matrix (r-Values) Based on Subject-Specific Data

	T_{END}	T_{RPE}	T_{MVE}[MD]	T_{MVE}[TRAP]	T_{MVE}[AD]
T_{RPE}	**0.66**				
T_{MVE}[MD]	0.34	0.31			
T_{MVE}[TRAP]	0.25	0.17	0.41		
T_{MVE}[AD]	0.33	0.22	**0.51**	0.47	
T_{MVE}[INFRA]	0.35	0.32	0.29	0.26	0.29

[A]Values ≥ 0.5, corresponding to $r^2 \geq 0.25$, are bold.

TABLE IV. Correlation Matrix (r-values) Based on Subject-Averaged Data

	T_{END}	T_{RPE}	T_{MVE}[MD]	T_{MVE}[TRAP]	T_{MVE}[AD]
T_{RPE}	**0.96**				
T_{MVE}[MD]	**0.81**	**0.77**			
T_{MVE}[TRAP]	**0.82**	**0.81**	0.68		
T_{MVE}[AD]	0.67	**0.78**	0.44	**0.90**	
T_{MVE}[INFRA]	**0.79**	**0.80**	0.38	**0.84**	**0.87**

[A]Values ≥ 0.7, corresponding to $r^2 \geq 0.5$, are bold.

TABLE V. Distribution of Endurance and Fatigue Times (Min)

Duty Cycle	%ile	T_{END}	T_{RPE}	T_{MVE}[A]
20/40	25	180	180	56
	50	180	75	41
	75	133	45	31
40/20	25	160	20	35
	50	90	10	17
	75	60	5	9

[A]T_{MVE} is the minimum across the four muscles.

general, poorly modeled. A stepwise regression procedure led to inclusion of three T_{MVE} values (no TRAP), with all model parameters significant ($P < 0.1$), normally distributed errors ($P = 0.77$, Shapiro-Wilk W test), and a small improvement in predicting T_{END} (r^2–adj = 0.60; standard error = 33.3 min; Figure 5).

DISCUSSION

This study was performed with a primary goal of determining endurance and fatigue limits when an overhead task is performed. Work tasks and/or workstations that lead to the development of shoulder fatigue were assumed to pose additional risk of musculoskeletal injury. Fatigue, given that its specific relationship with injury has yet to be determined, was viewed as an indicator or surrogate measure of risk, but it is emphasized that fatigue does not equal injury. Moderate levels of fatiguing work or exercise can be health promoting, and it is critical, though difficult, to identify loads that may impair health.[64,65] A therapeutic dose of exercise, however, is not typically of the same order of repetitiveness or prolonged loading as is commonly found in industrial tasks.[14,66] Fatigue leading to demonstrable effects was used here as a global indicator of potentially injurious underlying physiological processes. Measures of fatigue also combined the influences of external loads, moment arms, local energy expenditure, etc. By determining times at which fatigue first became evident, and when the task could no longer be continued, it was intended that the derived data could be used as a basis for evaluation of current tasks and also serve as a partial ergonomic guideline for design of future work.

Multiple measures were employed to provide a more comprehensive representation of the time-dependent changes occurring during the prolonged task performance. The classical approach to fatigue, now referred to as a failure point, represents an extreme physiological condition.[33,67,68] Although this failure point is typically obvious, and therefore easy to measure, it has limited utility if the design goal is to avoid fatigue in the more modern sense of an ongoing and gradual process. Despite existing data describing how the failure point relates to static effort levels, few would argue that tasks should be designed so that workers are at or near this level.

Adopting the viewpoint of fatigue as more continuous, however, implies that it does not have a distinct onset time, and no measures have been presented in the literature that conclusively indicate fatigue has occurred at a specific point. Several fatigue indices have been proposed.[69,70] Among these, indices with more statistical rigor have included tests on the slope of changes in action potential conduction velocity,[71,72] and iterative tests on a sequence of values.[73,74] A new operationalized indication of a fatigue onset was created here and used to determine when strength measures had changed by a defined amount. The defined amount of change was itself a function of the rate of change and the inherent data variability. Justification for this approach stems from the observation that confidence is higher that a real change has occurred when a measure exhibits both a large increasing or decreasing trend and stability (low variability) about this trend. A specific level of change could have been set a priori, such as 5% of maximum values,[75] but differences in data variability between subjects and measures argued against this approach. The method applied in this study explicitly accounted for differences in variability between subjects found both here and in earlier reports.[17] Although the fatigue process and its effects on strength are quite diverse,[76] and the T_{MVE} values used may be an oversimplification, discrete fatigue onset times can more directly be incorporated into design specifications.

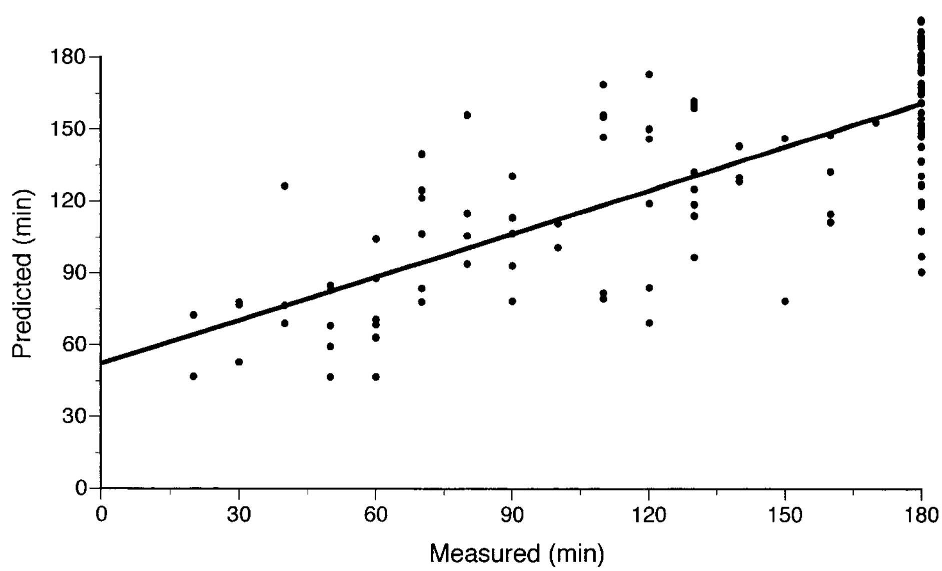

FIGURE 5. Relationship between measured and predicted T_{END}

The experimental tasks were intended to simulate exertions and postures common in industrial (assembly) work. In terms of stereotypical repetitiveness, the tasks were considered a good model, though they differ in several ways from actual overhead work. In particular, the tasks required close attention to both pacing and movement accuracy, whereas only a subset of jobs would impose both of these demands. Additionally, little freedom of movement was provided, in contrast to many assembly lines that allow (or require) walking and changing postures. Interruptions to the normal cycling of work and rest were needed to obtain MVE data. These interruptions, and the performance of MVEs every 10 min, may have biased the resulting data. That many of the participants could complete the experiment, particularly the less stressful conditions, with no perceptual or strength changes, suggests minimal bias by the inserted MVEs. It has also been reported that MVEs performed as often as once per minute had no influence on capacity after 30 repetitions.[52]

Although nearly a dozen muscles stabilize and generate movement of the shoulder mechanism, only four were examined due to experimental limitations and a need to minimize interruptions to the cyclic tasks. The four muscles studied are among the primary force generators, though fatigue, discomfort, and ultimately injury may involve the use of more underlying muscles. In particular, several reports have suggested an important role of the supraspinatus.[19,20,72,77] Postures used to obtain MVEs differed from those used during the experimental tasks. This difference was required for isolation of the muscles of interest, but may have led to some systematic errors in estimating strength capacity. Such errors were likely minimized, however, by the standardization of experimental protocols and use of within-subjects analysis of task effects.

Despite the limitations noted, the results indicate different fatigue events and how these varied with task configuration (Table V). Times at which the task could not be continued (T_{END}) provided an estimate of endurance, albeit with a ceiling level of 3 hours. Times at which fatigue was initially measurable were obtained from subjective (T_{RPE}) and strength (T_{MVE}) changes. Discriminating between fatigue onset and endurance is analogous to the approach taken by the National Institute for Occupational Safety and Health in the original construction of their guide for manual lifting,[78] in which action limits and maximum permissible limits are determined. The two limits are respectively interpreted as posing a moderately increased risk and a high risk requiring redesign.

Females, on average, performed the experimental tasks longer, developed perceptions of fatigue later, and showed less rapid decreases in strength than males. These results were somewhat surprising, and it is often assumed that endurance time is comparable between genders for equivalent exertion levels. Earlier studies[53] showed that males self-selected longer cycle durations at a given percentage of maximal exertion, and it was suggested that demand characteristics related to the gender of the experimenters may have influenced the results. It is possible that females were more motivated during the present experiments, though reasons for consistent gender differences are not obvious. Furthermore, sessions were typically conducted by both male and female experimenters.

The longer endurance times found among females are consistent with an earlier report that females had average endurance times 23% higher than males during sustained contractions at 40% MVE.[79] Female endurance times, during the more complex task described here, were 22% higher. It can be hypothesized that the differences are explained by intramuscular blood flow. The rapid decrease in endurance for tasks above ~15–20 MVE is generally thought due to a decline in blood flow subsequent to an increase in intramuscular pressure. If females and males exerted at comparable percentage levels, this suggests that endurance should be equivalent. There is evidence, however, that blood flow is more directly related to absolute versus relative force.[20] During the experimental tasks, males likely needed to generate larger shoulder moments due to longer segments, larger moment arms, and higher segment masses. If so, a stronger male, while exerting at comparable percentages of maximum (as found), would be generating larger muscle forces, and would thus have higher intramuscular pressures, greater reductions in blood flow, and shorter endurance times (as found). Despite these differences, and in the interest of providing data to facilitate design for mixed populations, design guidelines were developed and presented without further consideration of gender.

Of the task conditions studied, only duty cycle had consistent and substantial effects on fatigue and endurance. The influence of duty cycle agrees with earlier reports[80,81] and likely reflects the overall rate of energy use.[82] Lack of substantial effects of arm reach (target height) and hand orientation is surprising given the differences in muscle activity levels found between conditions and previous results suggesting a more dramatic influence of posture,[59,83] though these studies were of shorter duration. In two similar precision movement tasks, the same relative insensitivity to hand elevation was found for several movements involving different vertical locations,[53] and for movements at different locations above shoulder level.[61] It has been suggested that intermittent work and continuous static work are associated with different patterns of muscle recruitment. In contrast to a prolonged static effort, in which a consistent group of muscle and motor units within those muscles may be employed, changes in load sharing between muscle and motor unit recruitment and derecruitment may occur during intermittent or dynamic work.[67,84] Because muscle use in each condition was ascertained only at the start of each task, such changes could not be monitored.

The 20/40 duty cycle tasks could be completed by the vast majority of participants. During these apparently easy tasks, though, early signs of fatigue were revealed through changes in strength capability (T_{MVE}), occurring 30–60 min into the trial followed by subjective perceptions of fatigue (T_{RPE}). In contrast, few could complete the tasks with 40/20 duty cycles, and the perceptual changes preceded those based on strength. Perceptions of fatigue and discomfort are likely compilations of multiple underlying sources, of which localized muscle fatigue is only one, so it was not unexpected that differences between T_{RPE} and T_{MVE} were found. In addition, there are large individual differences in working technique[10] and muscle coordination.[85,86] It is not clear, however, what differences existed between duty cycles to explain the altered order of onset. Declining motivation during the longer lasting 20/40 tasks may have confounded measurements of underlying muscle strength measures, and led to underestimates of T_{MVE} during these tasks. It is also possible that perceptual measures (RPE) were more sensitive, and more likely to increase, during the 40/20 tasks in which fatigue accumulated during a single cycle predominates over that accumulated across cycles. In other words, the 40/20 duty cycle may cause more dramatic short-term withintrial increases in discomfort, versus more gradual intertrial increases occurring during the 20/40 duty cycle.

Measurement of endurance for a given task is time intensive and demanding of experimental participants. If these times could be predicted on the basis of earlier measures, both difficulties could be obviated. Although T_{END} did not show a one-to-one correspondence with any of the experimental measures, it could

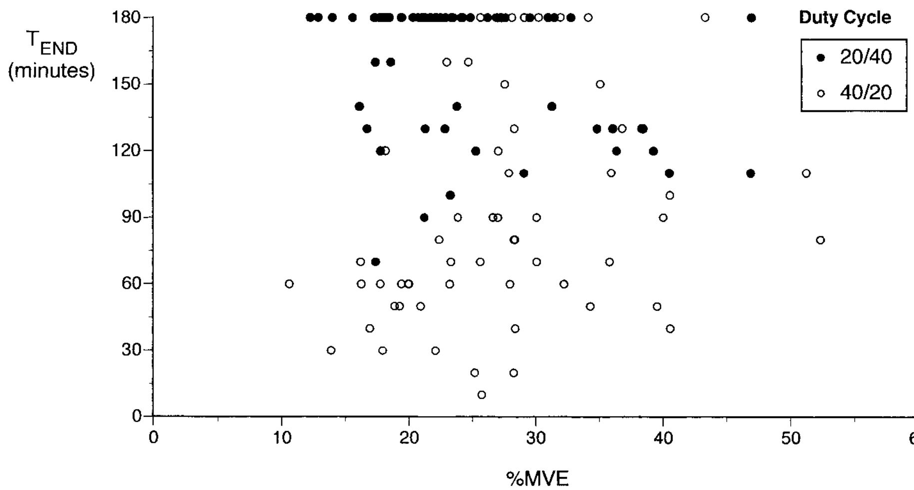

FIGURE 6. Relationship between T_{END} and %MVE (maximum across four muscles)

apparently be estimated within roughly 35 min using just RPE. This implies that at least a rough assessment of an overhead task can be obtained through simulation, determination of the time at which RPEs begin to rise, and extrapolation. A refinement of this estimation can be achieved by monitoring shoulder muscle strength (Figure 5), although it should be noted that substantial errors in estimation are possible. The results suggest that emphasis be placed on the deltoid muscle, given that signs of fatigue were more frequently apparent here than in either the TRAP or INFRA muscles. Initial analysis of the frequency content of the myoelectric signals during trials (not reported here), supports this emphasis, and also suggests that endurance time estimates can be further refined. In the absence of a quantitative indicator of injury risk, the lack of complete correspondence between the different measures need not be interpreted as a failing, and the correspondence does not appear to be as poor as has been suggested.[87] Alternatively, each measure is likely providing different forms of information, and each may have separate utility.

Although the experimental tasks were dynamic, muscle activity during the working portion of each cycle varied only on the order of ~10–30%. Although not a true static exertion, it is still useful to compare the results with existing data on the relationship between exertion level and endurance during intermittent tasks. A comparison of T_{END} to muscle activity (largest %MVE of all four muscles) reveals no obvious correspondence (Figure 6). This is in sharp contrast to the traditional descriptions of decreasing exponential relationships between endurance and relative muscle force,[42] and endurance times are below those previously suggested for comparable effort levels and duty cycles.[50] These results do not directly imply that such relationships are invalid, but rather support earlier reports that variability exists even during simple static exertions,[46] particularly during moderate exertions (10–40% of MVE). Furthermore, the present results and the noted discrepancies suggest that existing guidelines for intermittent static work limits may not be applicable to more complex (and realistic) tasks that involve intermittent dynamic levels of muscle activity within work cycles. For such tasks, more detailed models may be required that explicitly account for the temporal patterns of fatigue accumulation and recovery,[88–90] and individual differences in working methods and muscle physiology.

Straightforward extensions of this work include investigation of additional levels and number of task parameters. Examples include the influences of tool mass, prolonged rest periods, work experience, and age. The latter two may be of particular importance, given that workers typically undergo a process of physical adaptation and that typical industrial workers are older than the group investigated. Ongoing analysis will attempt to address several issues, including whether myoelectric measures are more consistent measures of fatigue during dynamic intermittent tasks; whether performance changes are correlated with other fatigue metrics; and the source(s) of the substantial interindividual differences observed.

CONCLUSIONS

This study demonstrated that duty cycle is a critical parameter to address in the design and analysis of work tasks. In contrast, arm reach and hand orientation have relatively minor influences on endurance or subjective discomfort. Among the muscles studied, the anterior and middle portions of the deltoid appeared the most susceptible to fatigue. Rough estimates of endurance could be obtained from simple (subjective) assessments, and thus appear suitable for rapid evaluation or screening. Observed gender differences suggest that females develop fatigue less rapidly than males when performing at similar percentages of capacity. Cautions are suggested when applying traditional endurance-effort relationships to complex (intermittent and dynamic) tasks, as they may not account for substantial interindividual variability.

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