Ergonomics
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/terg20

Fatigue during prolonged intermittent overhead work: reliability of measures and effects of working height

Deepti Sood [a] , Maury A. Nussbaum [a] & Kris Hager [a]

[a] Industrial and Systems Engineering, Virginia Tech , 250 Durham Hall (0118), Blacksburg, VA, 24061, USA

Published online: 21 Feb 2007.

Ergonomics
Vol. 50, No. 4, April 2007, 497–513

Fatigue during prolonged intermittent overhead work: reliability of measures and effects of working height

DEEPTI SOOD, MAURY A. NUSSBAUM* and KRIS HAGER

Industrial and Systems Engineering, Virginia Tech, 250 Durham Hall (0118), Blacksburg, VA 24061, USA

Shoulder pain is prevalent among industrial workers and existing evidence supports that overhead work is an important specific risk factor. Existing guidelines are limited, with overhead work typically recommended to be avoided, and research on overhead work has been mixed in terms of the effects of increasing arm reach. A laboratory-based simulation of overhead work was conducted, at three working heights, in order to facilitate improved guidelines and to identify potential non-linear effects of overhead work height. Several indicators of shoulder fatigue served as outcome measures and a preliminary study was performed to assess the reliability of several of these measures. Fatigue measures based on electromyography (EMG) generally had low reliability, whereas excellent reliability was exhibited for ratings of perceived discomfort (RPD). Consistent with this, no effects of overhead work height were found on EMG-based measures, yet clear non-linear effects were found on RPD and task performance. The source of the effects of work height appeared to be related to a combination of muscle activation levels and demands on precision/control at the highest location. These results support the utility of subjective measures for relatively low-level intermittent exertions and demonstrate increasingly detrimental fatigue and performance effects at extremes in reach during overhead work.

Keywords: Fatigue; Overhead work; Intermittent work; Shoulder; Reliability; Electromyography; Perceived discomfort

1. Introduction

Existing evidence suggests a relatively high prevalence of shoulder pain among industrial workers (Allander 1974, Maeda 1977, Kourinka and Koskinen 1979, Brox 2003, Sommerich and Hughes 2006). Contemporary trends in the design of work tasks include increasingly simplified and repetitive yet less strenuous work, much of which involves the

*Corresponding author. Email: nussbaum@vt.edu

Ergonomics
ISSN 0014-0139 print/ISSN 1366-5847 online © 2007 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/00140130601133800

upper extremity. Such trends may explain why the prevalence appears to be increasing (Sommerich *et al.* 1993). Several studies have found relationships between the development of shoulder musculoskeletal disorders (MSDs) and work exposures, including static efforts, insufficient recovery or rest and non-neutral postures (National Institute for Occupational Safety and Health 1997). While risk factors for shoulder MSDs appear to be complex and multifactorial, repetitive overhead work (defined here as working with a hand above the head) appears to be an important specific risk. Extensive convergent evidence for this exists from epidemiological, physiological and biomechanical investigations on overhead work per se, as well as upper extremity elevation (Herberts and Kadefors 1976, Bjelle *et al.* 1979, 1981, Kilbom *et al.* 1986, Hagberg and Wegman 1987, Ohlsson *et al.* 1995, Sakakibara *et al.* 1995, Punnett *et al.* 2000, Björkstén *et al.* 2001, Svendsen *et al.* 2004a,b).

Several pathophysiological mechanisms have been proposed to link overhead work and shoulder MSDs. Hagberg (1984) suggested that work requiring arm elevation impairs circulation and compresses tendons, thereby accelerating rotator cuff degeneration. Intramuscular pressure increases with arm elevation (Järvholm *et al.* 1991), which in turn impairs local muscle blood flow (Järvholm *et al.* 1988b). Järvholm *et al.* (1988a) further suggested that fatigue and shoulder pain related to elevated arm positions may result from intramuscular pressure-induced ischaemia. It is notable that these intramuscular pressure-related effects were observed with no external loads and that effects further increased with hand loads (Järvholm *et al.* 1988a). Arm elevation resulting from overhead work can also lead to mechanical impingement of subacromial tendons (Flatow *et al.* 1994), with additional injury risk imposed by the poor vascularization of rotator cuff tendons (Lohr and Uhthoff 1990).

In contrast to the evidence linking overhead work with shoulder MSDs, there remains a lack of formal guidelines for situations where such work cannot be avoided, specifically related to whether certain overhead working heights may be more disadvantageous in terms of MSD risk and performance. A review of common text books and other sources indicates that overhead work height is usually considered categorically (i.e. overhead work exists or does not) and that it is to be avoided if possible. Other sources consider overhead work height using a single criterion value, for example, highlighting increased risk when shoulder abduction or flexion exceeds 60° (National Institute for Occupational Safety and Health 1997).

A number of studies have been conducted that can contribute to the type of overhead work guidelines noted, although inconsistencies exist. For precision movement tasks, several studies have indicated little or no effect of hand elevation (Wiker *et al.* 1989, Putz-Anderson and Galinsky 1993, Nussbaum *et al.* 2001). In contrast, overhead work height was found to significantly increase shoulder muscle activity and moments (Anton *et al.* 2001) and perceived discomfort (Ulin *et al.* 1990). In order to supplement this existing evidence, as well as to identify potential non-linear effects of overhead work height, the current study assessed three heights during simulated overhead work. Indicators of localized muscle fatigue (LMF) served as outcome measures. Given mixed evidence for some of these indicators in terms of reliability (e.g. Nagata *et al.* 1990, Gamet *et al.* 1993, Elfving *et al.* 1999) and the lack of such evidence in the context of intermittent overhead work, a preliminary study was conducted to quantify reliability of several subjective and objective fatigue indices. It was anticipated that some measures would be more reliable than others, and such results were used to guide interpretation of results obtained from the main study on overhead work height.

2. Methods

Two experiments were conducted, the first to determine the reliability of several objective and subjective measures used to directly or indirectly assess localized shoulder fatigue and the second to determine the influence of task height on fatigue during intermittent overhead work. Both experiments used laboratory simulations, designed based on observations made at an automotive assembly plant and with levels of the tasks parameters described below consistent with values or ranges observed. An overhead tapping task was used in both experiments, which was considered representative of common overhead occupational task demands by inclusion of precise movements to targets and obstacle avoidance. This is illustrated in figure 1.

2.1. *Experiment 1: Reliability of measures*

2.1.1. Experimental task. Participants stood underneath a height-adjustable overhead platform (with a maximum height of 263 cm), set according to individual anthropometry (as described below). A keyboard was attached to the bottom of this platform, oriented horizontally and with the keys pointing downward. A modified, non-functional electric drill (mass = 1.25 kg), into which a wooden dowel was chucked, was used to tap the keys on the keyboard. Four designated keys were tapped in a defined sequence, which was indicated by numbers 1–4 marked on the S, 5, L and U keys. A rubber hose was attached to the drill (diameter = 2.0 cm, mass = 0.28 kg/m), simulating the weight of a pneumatic or electric power supply line. Two thin, rigid wires were strung over the keyboard, 3 cm below the key tops and 10 cm apart, to force vertical movements of the drill (thereby simulating obstacle avoidance).

Task height was derived from two anthropometric measures of the dominant hand/arm: hand height with the shoulder and elbow flexed to 90° in neutral upper arm rotation (A), and hand height with the upper arm in full flexion (maximum overhead reach) with shoulders parallel to ground (i.e. no shoulder elevation) (B). Hand height was measured to the centre of the grip as the participant held the same drill that they used in the overhead tapping task. For the first experiment, the platform height was set so that the hand height was $A + 0.40(B - A)$, corresponding to a midpoint between the two extreme values of hand height, which were tested in the second experiment (and illustrated in figure 2).

The tapping task was performed intermittently, using the dominant arm, with a cycle time of 54 s and a 50% duty cycle. The first half of each cycle consisted of 27 s of work, involving repetitive key tapping. This was followed by 27 s of 'rest', during which the tool was placed in a holder and the participant performed light manual work at waist height, involving screwing and unscrewing nuts and bolts. Fixed pacing for the key tapping was achieved by using a digital metronome set at 80 beats per min. Hence, this pace required 36 key taps per work cycle (with nine repetitions of the four-key sequence noted above). This was selected based on preliminary work to provide a moderate psychomotor challenge. Onset and termination of the work cycle was controlled using computer-generated auditory signals. Participants freely selected their postures throughout the experiments and were allowed to adjust their postures as desired.

2.1.2. Experimental design and participants. Two sessions were used to determine between-days, test–retest reliability of several measures obtained during the overhead tapping task. Sessions were separated by 2–7 d. For each participant, the two sessions

Figure 1. Participant shown performing the overhead task (with the hand height corresponding to middle height in figure 2).

were conducted at a similar time during the day (e.g. afternoon) and by the same experimenter.

Potential participants were recruited from the university and local community. Ten participants (five males and five females) were involved, with a mean age of 24.2 (SD 2.7)

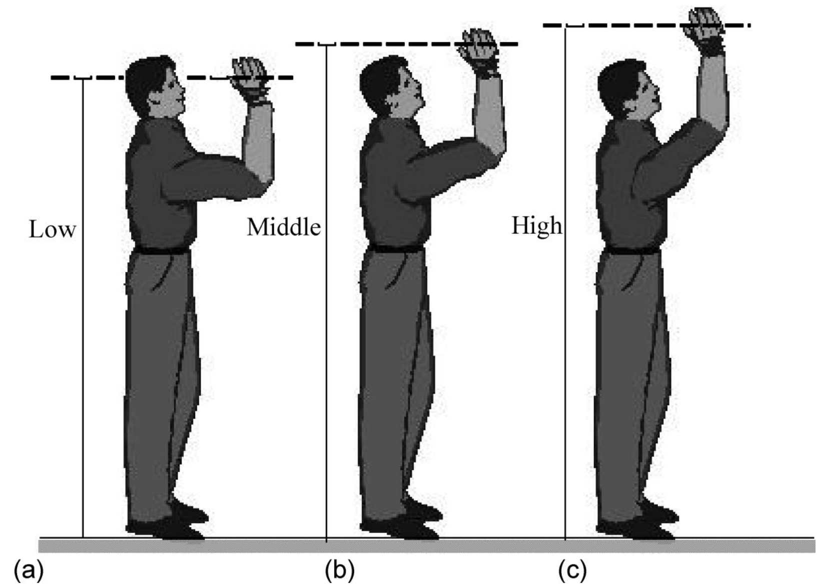

Figure 2. Illustration of the three overhead work heights. a), low; b), middle; c) high.

years. All were right hand dominant. Stature and body mass were 175.74 (SD 5.71) cm and 72.52 (SD 10.02) kg, respectively. All participants reported either recent manual work experience or performance of upper extremity exercise on a regular basis. None of the participants reported any recent injuries (within the last 12 months) or any musculoskeletal problems that might have influenced their performance.

2.1.3. Experimental procedures. Participants provided written informed consent using procedures approved by the Virginia Tech Institutional Review Board. Following this, a videotape recording was shown of selected overhead assembly tasks, from an automotive plant, to provide familiarization with the 'real world' equivalent of the experimental task simulations.

Surface electromyography (EMG) was obtained from three accessible shoulder muscles: anterior deltoid; medial deltoid; and upper trapezius. These muscles were selected because prior evidence indicated their recruitment and susceptibility to fatigue during overhead work (Gerdle *et al.* 1988, Nussbaum, 2001). Pairs of pre-gelled bipolar Ag/AgCl electrodes (1 cm diameter), with a 2.5 cm inter-electrode distance, were placed midway between the lateral third of the clavicle and the deltoid insertion for the anterior deltoid, midway between the acromion and the deltoid insertion for medial deltoid, and 2 cm lateral to the midpoint of a line connecting the C7 spinous process and the acromion for the upper trapezius. Adjustments to these electrode positions were made to ensure placement on the muscle belly and orientation parallel to muscle fibres. A reference (ground) electrode was placed on the clavicle. Prior to electrode placement, the skin was shaved, lightly abraded and cleaned with 70% rubbing alcohol. Impedance between electrode pairs was kept below 10 kΩ (measured after a 10 min stabilization period) and distances from bony landmarks were measured and maintained across experimental sessions. Raw signals were preamplified ($\times$100) near the source, amplified to a range near ± 5 V and hardware filtered (10–500 Hz). Raw and root mean square (RMS; 110 ms time constant) values were sampled at 2048 Hz and 128 Hz, respectively.

In each session, maximum voluntary contractions (MVCs) were obtained from the dominant arm in postures intended to isolate the three shoulder muscles. The procedures are described in Nussbaum *et al.* (2001). During MVC trials, forces were obtained using a load cell (AMTI, Watertown, MA, USA, model MSA-6–250) sampled at 2048 Hz. It should be noted that, since analyses in both experiments were made 'within-participants', forces were considered an adequate dependent measure, without a need for determining net shoulder moments. EMG data were also collected, with maximal RMS values used later for normalization. At least three MVC trials per muscle were performed, with a minimum of 1 min rest between trials. MVC trials were conducted until the maximum force exerted in a subsequent trial was lower than the maximum force exerted in a previous trial, and the maximum value across all trials was recorded as the MVC.

Participants used an existing 10-point scale (Borg 1982) to rate their level of perceived shoulder discomfort. An initial practice session using the scale was employed, involving holding a 0.5 kg mass in the non-dominant arm, while the arm was abducted to 90°. Standardized instruction was provided on the use of the scale, in particular to focus on perceptions localized to the shoulder. Participants held the posture while providing ratings of perceived discomfort (RPDs) every 5–10 s until reaching their endurance limit (or until a 10 was reported on the scale). Such practice was believed, based on prior pilot work, to facilitate better conceptualization of the scale and to improve reliability by 'normalizing' participants' ratings over the full range of the scale (0–10).

After 10 min of rest, 5 min of practice was provided on the overhead tapping task, a duration considered sufficient for procedural familiarization without the addition of shoulder fatigue. Following task practice, participants rested for 5 min or until $\text{RPD} = 0$ was reported. Participants then began the tapping task. EMGs were recorded during the last 6 s of the tapping portion of each cycle. RPDs were provided every fifth cycle (or every 4.5 min). The task was continued until one of the following stopping criteria was met: 1 h had elapsed; participant reported $\text{RPD} \geq 9$ on two consecutive samples; or participant reported $\text{RPD} = 10$.

2.1.4. Response variables and analysis. Three categories of response variable were obtained: MVCs for each muscle; EMG-based measures; and shoulder RPDs. EMG RMS values were averaged over the sampling period and normalized to maximal values obtained from MVCs, while raw values were processed to obtain mean (MPF) and median (MDF) power frequencies. Temporal changes in the RPD and EMG measures were interpreted as indicative of fatigue. As these were generally linear, slopes from linear regression were used to characterize temporal changes. Intercepts derived from regression were used to more reliably estimate the initial values of the EMG-based measures, whereas the level of discomfort at task termination was assessed using the final reported RPD.

Reliability of each measure was evaluated using three indices: intraclass correlation coefficient (ICC); standard error of measurement; and coefficient of variation (CV). ICC, a measure of relative reliability, examines between-participant variability vs. within-participant variability (Denegar and Ball 1993). ICC (2,1) was estimated following Shrout and Fleiss (1979) and can range from 0 (no reliability) to 1 (perfect reliability). A negative ICC indicates that the within-participant variance has exceeded the between-participant variance and is equivalent to an ICC of 0. ICCs were interpreted qualitatively using the following scheme (Bartko 1976, Stokdijk *et al.* 2000): 0–0.39 = poor; 0.40–0.59 = fair;

0.60–0.79 = good; 0.8–1.0 = excellent. A measure of absolute reliability, SEM, was reported along with ICC to check for cases where ICC might overestimate reliability. SEM estimates the precision of a measure (Denegar and Ball 1993) and is determined as [$s\sqrt{(1 - ICC)}$], where s is the standard deviation. A high value of SEM, in relation to the measurements, indicates a high level of error, which in turn implies non-reproducibility of tested values. The final measure, CV, defined as [(SEM/mean) $\times$ 100], allowed for comparisons between different variables and methods by scaling the SEM to the mean (although it is notable that alternative definitions of CV exist).

2.2. *Experiment 2: Effect of working height on shoulder fatigue*

2.2.1. Experimental task and procedures. The same overhead tapping task was used as described for experiment 1. Three working heights were examined, with each determined relative to each participant's anthropometry (as illustrated in figure 2). The middle height was determined as described earlier. The lowest height was set at A and the highest height was set at [$A + 0.80\ (B - A)$]. This value for the highest height was intended to avoid limits to the range of motion and associated high levels of force developed in passive shoulder tissues. Preliminary observations also indicated that this height led to the use of primarily shoulder motion, as opposed to torso and lower body motions used at higher levels.

All participants attended four sessions, separated by 2–7 d, which included one practice session and three experimental sessions (one at each height). Except as indicated below, experimental procedures, data collection and data reduction were the same as described for experiment 1. In the practice session, 5 min of practice was provided at all three heights, with the order determined using balanced Latin Squares, and the same order was used in the experimental sessions. Participants then practised at the last height in the treatment order for 1 h or until they experienced substantial discomfort (RPD > 9). These practice procedures were developed in order to provide familiarization, both with different heights and with experimental procedures involving continuation of the task for a prolonged time, and to minimize carryover effects.

In the three experimental sessions, 'task-specific' MVCs were conducted, in order to determine if there was a relationship with endurance/fatigue. Additional MVCs, as described for experiment 1, were also obtained for EMG normalization. To obtain task-specific MVCs, participants pushed upward against the overhead platform, the height of which was set at a level to replicate the postures used while tapping at the height specified for that session. Participants stood on a force platform (OR6; Advanced Mechanical Technology Inc., Watertown, MA, USA), which was used to obtain peak vertical forces (recorded at 2048 Hz) after subtraction of body weight. As in experiment 1, at least three task-specific MVC trials were conducted, with a minimum of 1 min rest between trials. After a rest period, practice was provided at the specified height, additional rest was given and then the tapping task was performed until one of the stopping criteria noted earlier was met. Key taps were recorded during each work cycle, comprising nine sets of the sequence of four marked keys (a total of 36 key taps). The number of errors made in each work cycle was determined, to indicate changes in performance during the prolonged task, where errors consisted of missed keys, double hits or incorrect key hits.

2.2.2. Participants. A total of 12 participants (six males and six females) were selected, based on a priori power analysis to detect a 'large' effect (Keppel 1991). This sample size also allowed for a complete replication of the balanced design for each gender. Participant selection criteria were the same as for experiment 1 and the participants' stature and body mass were 172.8 (SD 8.8) cm and 71.7 (SD 13.9) kg, respectively. Mean age was 27.3 (SD 8.0) years and length of reported employment was 4.7 (SD 9.7) years (the latter distribution being right-skewed).

2.2.3. Response variables and analysis. Temporal changes in EMG-based measures were determined from linear regression slopes. RPD onset times were used to determine the progression in reported shoulder discomfort, derived as the earliest time at which specific RPD levels were reported (i.e. 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5). Key tap errors were highly variable across work cycles. In order to analyse error trends, trials were divided into thirds and errors made in each third were combined to yield an error rate (per cycle) in each third of a trial. Separate repeated measures ANOVA was used to identify statistically significant factor effects (gender, working height and their interactions) on each response variable. Factor effects, and post-hoc comparisons made using Tukey's HSD, were considered significant when $p < 0.05$.

3. Results

3.1. *Experiment 1: Reliability of measures*

Table 1 summarizes the three indices of reliability for MVC and EMG-based variables along with mean values for each. ICC values for MVCs of all three muscles were quite high and were complemented by low SEM and CV values. Among the EMG-based measures, only initial values of MPF and MDF demonstrated good – excellent reliability for all muscles and good agreement between the reliability indices. As indicators of fatigue, slopes of both MPF and MDF had reliability that ranged from poor to excellent. Spectral measures tended to be more reliable than RMS, although this difference varied between muscles. Across muscles, EMG-based measures were typically more reliable for the medial deltoid. Such generalizations, however, must be made with caution due to the frequent qualitative disagreement between the three reliability measures.

Mean final reported and rates of change of RPD ratings were 3.9 and 0.05/min, respectively. All participants completed the 1 h sessions (that is, the trials were not stopped due to high levels of RPD). ICCs indicated excellent reliability of final RPDs ($ICC = 0.86$) and RPD slopes ($ICC = 0.92$) and these were supported by relatively low levels of SEM (0.77 and 0.008/min, respectively) and CV (19.6 and 16.9, respectively).

3.2. *Experiment 2: Effect of working height on shoulder fatigue*

3.2.1. Maximum voluntary contractions and electromyography. Order effects on the task-specific MVC values were not significant ($p > 0.87$). Significant height effects on the task-specific MVCs were present ($p < 0.001$). Specifically, mean vertical forces were 192.8 (SD 85.5) N for the low work height, 227.8 (SD 81.9) N for the middle height and 429.5 (SD 228.4) N for the high height, with low and middle work heights not significantly different ($p = 0.38$). A significant ($p = 0.0003$) gender × height interaction effect was found on the task-specific MVCs, wherein gender differences (males > females) were most evident at the highest level. None of the EMG-based fatigue measures obtained during the experimental task showed any significant main or interactive effects of task height or any consistent trends.

Table 1. Mean values and reliability of maximum voluntary contraction (MVC) and electromyography (EMG)-based measures.

		Anterior deltoid				Medial deltoid				Upper trapezius			
Measure	Parameter	Mean	ICC	SEM	CV	Mean	ICC	SEM	CV	Mean	ICC	SEM	CV
MVC (N)		165.1	0.96	11.9	7.2	214.9	0.95	16.0	7.5	655.9	0.97	27.1	4.1
MPF	Intercept (Hz)	92.0	0.79	7.2	7.8	98.5	0.81	5.6	5.7	100.7	0.48*	7.9	7.8
	slope (Hz/min)	−0.035	0	0.070	203.4	0.016	0.72*	0.063	385.2	−0.017	0.64*	0.032	183.0
MDF	Intercept (Hz)	81.8	0.63	8.5	10.5	86.0	0.83	5.0	5.8	92.7	0.72	5.8	5.8
	slope (Hz/min)	−0.036	0	0.057	160.3	0.024	0.80*	0.054	222.9	−0.016	0.68*	0.029	205.9
RMS	Intercept (% max)	21	0.79	3.7	17.5	17	0.38*	5.7	33.5	15	0.60	3.9	25.9
	slope (%/min)	0.006	0.64*	0.026	411.7	.032	0.78*	0.026	80.9	−0.001	0.27*	0.030	2479.7

*Indicates disagreement between intraclass correlation coefficient (ICC) and SEM or coefficient of variation (CV).
CV has units of %.
MPF = EMG mean power frequency; MDF = EMG median power frequency; RMS = normalized EMG root mean square.

3.2.2. Ratings of perceived discomfort. Ten of the 12 participants were able to complete the task (for 1 h) at all three heights. The highest final reported RPD was less than 5 at all three heights for nine of the 12 participants. The times at which selected values of shoulder discomfort (RPD) were reported were different for the three working heights (figure 3). Compared to the low and middle heights, a given level of discomfort was generally reported earlier when the task was performed at the high work height. Very low levels of perceived discomfort (RPD = 0.5) appear to have occurred latest at the middle height, while moderate levels of discomfort (RPD = 1.0–3.5) occurred latest at the low height. The effect of height, however, was significant only for RPD = 2.5 ($p = 0.03$). Trends in the effect of height were evident for RPD = 1.0 ($p = 0.08$), RPD = 1.5 ($p = 0.06$), RPD = 2.0 ($p = 0.08$) and RPD = 3.5 ($p = 0.06$). Height effects were not significant for RPD = 0.5 ($p = 0.66$) or RPD = 3.0 ($p = 0.11$). Order effects were not significant for any of the RPD levels ($p > 0.52$), except for RPD = 0.5. There were no significant gender effects on RPD onset times ($p > 0.69$) and no significant gender × height interactions ($p > 0.18$).

3.2.3. Task (key tapping) performance. Indications of initial decreases in errors (occurring during the first 10–15 min) were present for tapping at the low and high heights, but these trends were not significant across trials ($p = 0.86$). Significant ($p = 0.03$) decrements in performance (increased error rates) were observed with increasing work heights (figure 4). Females overall made more frequent errors than males, with mean values of 4.51 (SD 2.54) and 3.12 (SD 2.74) errors/cycle, respectively, although the gender effect was not significant ($p = 0.10$). A significant gender × height interaction was found ($p = 0.014$), wherein gender differences decreased with height. Specifically, females had 91, 45 and 15% higher errors rates at the low, middle and high work heights, respectively.

4. Discussion

Given the recognized problem of shoulder pain among industrial workers, and evidence for overhead work as an important risk factor, the current research represents part of an

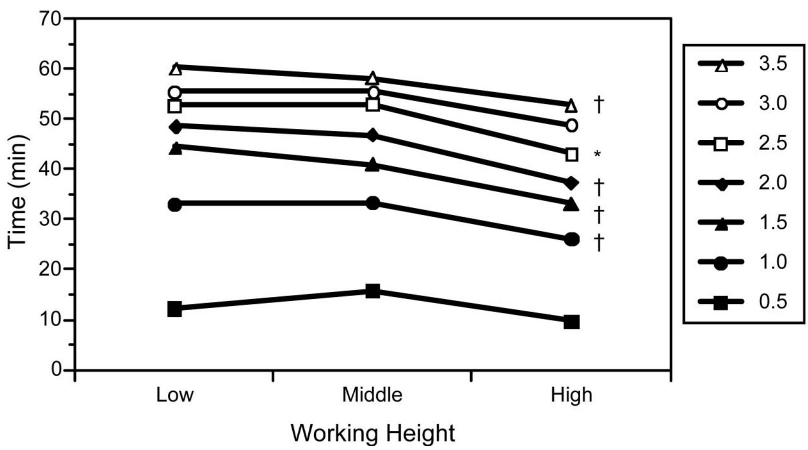

Figure 3. Mean times at which several rating of perceived discomfort levels were reached for each working height (n = 12). *Indicates significant effect of working height. †Indicates trends. (Standard deviations not shown for clarity, range = 13–27 min.)

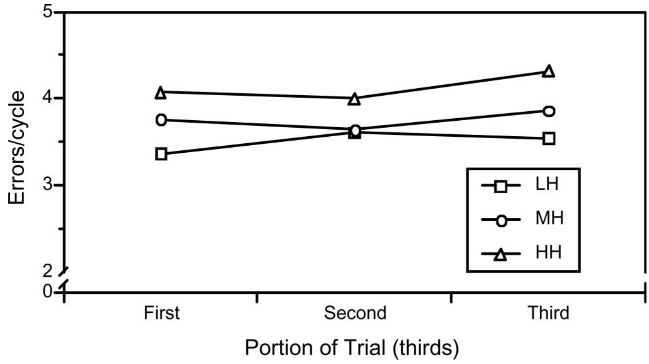

Figure 4. Mean error rates during key tapping at three working heights, low height (LH), middle height (MH) and high height (HH) in each third of the trial. (Standard deviations not shown for clarity, range = 2.3–3.3 errors/cycle.)

ongoing effort to derive practical guidelines for such work. This research was also motivated by the lack of specificity in contemporary guidelines regarding the effects of working height and mixed evidence from studies that have explicitly addressed overhead work. A central assumption was that LMF, whether measured using subjective or objective measures, is a valid approach in assessing injury risk (or in developing guidelines). Causal relationships between LMF and occupational injury have been proposed (e.g. Armstrong *et al.* 1993, Sejersted and Vøllestad 1993, Öberg *et al.* 1994). It is acknowledged, however, that LMF development does not necessarily equate to injury and that complex temporal factors are likely involved. In contrast, LMF can be argued to be a surrogate indicator of risk (Nussbaum 2001) and/or a biomarker for complex cumulative exposures (Dennerlein *et al.* 2003). Support for this stems from the relationships (or responsiveness) of LMF to several more fundamental and acknowledged risk factors, such as force, repetition and duration, as well as from the adverse influence of LMF on comfort and performance (Herberts *et al.* 1980, Wiker *et al.* 1989, Hammarskjöld and Harms-Ringdahl 1992).

Earlier work suggested potential concerns regarding the reliability of some LMF indices and indicated a lack of such evidence in the context of overhead work. Strength measures (MVC) were employed here only indirectly in assessing LMF, in order to normalize EMGs. MVCs exhibited excellent reliability, with very low error estimates, consistent with earlier reports (Elfving *et al.* 1999, Dvir and Keating 2001, Rainoldi *et al.* 2001). Although not assessed directly, reliability of the task-specific MVCs performed in the main study was supported by the lack of any order effects.

The tasks studied here involved relatively low levels of exertion, which were intermittent and dynamic. In such conditions, EMG-based measures have, in general, been found inconsistent or contradictory in terms of the expected changes in these measures (e.g. Nagata *et al.* 1990, Gamet *et al.* 1993). Here, the reliability of EMG RMS, both initial values and temporal changes, was quite variable across muscles, ranging from fair to high, similar to earlier reports (Sleivert and Wenger 1994, Larsson *et al.* 1999, Arnall *et al.* 2002). Initial values of EMG spectral measures had generally high reliability and a good correspondence among the three muscles tested, whereas the temporal changes exhibited lower reliability and more variability between muscles, both of which are again consistent with earlier reports (e.g. Elfving *et al.* 1999, Dedering *et al.* 2000, Rainoldi *et al.* 2001). The present results are likely due to the low exertion levels involved in the overhead work tasks (~15–20% MVC), which is associated with low EMG reliability (Nargol *et al.* 1999). Additional analyses were conducted using both normalized and absolute values of temporal changes. As has been found by others (Dedering *et al.* 2000, Larivière *et al.* 2002), there was no clear improvement in estimated reliability.

In contrast to EMG, the subjective measure (RPD) demonstrated excellent reliability for both final reported values and temporal changes. Each of the three measures of reliability for final reported RPD were surprisingly similar to those reported by Elfving *et al.* (1999) after a 45 s isometric trunk extension (ICC = 0.84; SEM = 0.8; CV = 17%), despite the obvious differences in protocols from the current study. In the replication of the overhead tapping task, participants appeared to reach similar discomfort levels after 1 h and the rate of increase in discomfort was also similar between sessions. Both support the validity of this measure as an indicator of LMF, as does earlier work showing that the development of discomfort is well correlated with endurance time in both a static task (Dedering *et al.* 1999) and a comparable overhead task (Nussbaum *et al.* 2001).

No effects of working height during the overhead tapping tasks were found for any EMG-based measures and this can be explained by the above noted limitations in reliability, lack of sensitivity or potential confounding effects. An earlier study (Nussbaum *et al.* 2001), involving a tapping task on a vertically oriented overhead target, similarly found only marginal effects of height on EMG-based fatigue indices. Results of Wiker *et al.* (1989) are also consistent, in terms of a lack of sensitivity of EMG-based measures to working height.

Clear, and non-linear, effects of working height were indicated by RPD measures. Onset times for low–moderate levels of discomfort (RPD = 1–3) were generally later at heights in the low–middle range of overhead reach capacity, indicating a more rapid development of fatigue with more extreme reaches. The detrimental effect of higher work locations, in terms of perceived discomfort, has been reported earlier (Wiker *et al.* 1989, Ulin *et al.* 1990, Nussbaum *et al.* 2001). What is the underlying mechanism, however, to explain the effect of working height? Increases in relative muscle activation occur with more extensive overhead reaches (Anton *et al.* 2001, Nussbaum *et al.* 2001). Since endurance time has an inverse relationship with muscle activation level (e.g. Rohmert 1960), the more extreme reaches can be expected to lead to more rapid fatigue development and reduced endurance times. These increases in activity with working height, however, are somewhat counterintuitive, since with increasing reach (as in figure 2), external moments at the shoulder decrease. Several additional mechanisms are likely to be involved. Additional muscle force is needed to equilibrate the increasing involvement of passive tissues with higher reaches. In the current tapping tasks, movements in the horizontal plane were similar at each elevation, yet the increasing elevation led to smaller angular movements between keys. Smaller movements require more control, which may be achieved by increasing co-contraction of the shoulder muscles. The need for higher levels of control is corroborated by the increased error rates observed at the higher task levels and evidence that shoulder muscle activity increases with the addition of precision required for a manual task (Sporrong *et al.* 1998).

The observed non-linear influence of overhead work height on perceived discomfort and error rates can only be partially explained by the levels of relative muscle activity. Here, muscle activity was estimated as the intercept values from linear regression of normalized RMS values vs. time. Activity of the anterior deltoid and medial deltoid were significantly affected by working height, increasing from 22.1 to 27.0% MVC and 16.1 to 24.4% MVC, respectively, from the low height to the high height. Post-hoc comparisons yielded two groups for each muscle, specifically (low and middle heights) and (middle and high heights). There was no indication of non-linear changes in muscle activity with increasing height ($p > 0.58$ from quadratic trend analysis). Given the roughly exponential relationship between muscle activity (%MVC) and endurance time (Rohmert 1960), a linear increase in muscle activity with working height should result in a non-linear decrease in endurance time (and an increase in fatigue rate). These arguments suggest, however, that the effects of working height should have been most apparent in moving from the low to the middle height, whereas the present results indicated the effects were most prominent when moving from the middle to the high height. Issues noted above, related to precision and control, are a likely explanation for the observed trends and are supported by the more substantial effects of extreme reaching (at the high work height) on task errors (figure 4).

While consistent results were obtained for the effects of overhead work height on perceived discomfort and errors, there are clear discrepancies with the task-specific MVCs obtained. At the most extreme reach (high work height), participants exerted nearly twice the upward force that was exerted at the other two levels. Since the same tool was used in all cases, it is logical to suppose that the relative demands imposed at the high height are smallest and, in turn, that fatigue development would be slowest. It may be, however, that the muscles used for the short task-specific MVCs are not the same as those used during the tapping task, that this, difference is more pronounced in the most extreme reach, or that the effects of increasing precision at the high height were predominant. In any case, use of such task-specific measures to estimate task performance is clearly not supported (that is, relative strength does not directly relate to relative fatigability with changing task height). The present results are also inconsistent with those of Garg *et al.* (2002), who indicated that endurance time decreased with increases in shoulder flexion up to 120° (comparable to the middle height condition in the present study) and then increased. It may be that the static, relatively constrained postures in their study are not comparable with the present dynamic and intermittent task, in which participants had a fair degree of flexibility in using postural adjustments.

Performance, assessed here as tapping error rates, exhibited effects of overhead working height that were consistent with perceived discomfort. Specifically, error rates tended to increase with time, particularly at the most extreme reach (high work height). This association between fatigue and decreased performance supplements existing evidence in several diverse contexts (Chaffin 1973, Wiker *et al.* 1989, Hammarskjöld and Harms-Ringdahl 1992, Jaric *et al.* 1999). Performance decrements over time may be caused by LMF, resulting from fatigue-induced decrements in proprioception (Carpenter *et al.* 1998, Björklund *et al.* 2000) or increases in force fluctuations (Hunter and Enoka 2003), although confounding attentional influences cannot be ruled out. This relationship between fatigue and performance is considered important, since performance changes, or decreases in task quality, have the potential for justifying and driving ergonomic changes.

Several limitations are inherent in the present study. Although the supraspinatus muscle is often a focus in the study of occupational shoulder injuries, this muscle was not monitored in the present study as it is not accessible by surface EMG. It can be anticipated, however, that supraspinatus EMG would have been similarly unreliable and insensitive as the results found here for other shoulder muscles. More generally, it is inherently assumed here that a focus on muscles is warranted (e.g. as opposed to tendon loads). Support for this focus comes from Madeleine *et al.* (1998), who found that injections of hypertonic saline in the trapezius or infraspinatus muscles led to pain that was similar to that occurring with chronic work-related neck/shoulder pain and concluded that the latter pain is likely muscular in origin. A single case of overhead work was studied here and the main conclusion, that more extreme reaches during overhead work are detrimental, may not be generalizable to all cases. Generality is supported, however, by the similarity of findings here, using a horizontal surface, to those in an earlier study (Nussbaum *et al.* 2001) using a vertical surface.

5. Conclusions

In summary, RPDs exhibited excellent reliability (high ICC, low SEM and CV) during performance of an intermittent overhead work (key tapping) task. In contrast, the reliability of EMG-based measures was relatively lower. Working height was found to have significant effects on the rate at which perceived discomfort increased. This height effect was non-linear, with the highest rates observed at the most extreme reaches. A similar effect was found on performance, quantified as the errors made during the tapping task. In contrast, no effects of working height on EMG-based fatigue measures were found (consistent with the observed lower levels of reliability) and task specific capacity (MVC) was not predictive of the discomfort trends. Levels of muscle activation, along with demands on precision and control, appeared to explain both the overall effect of working height and the non-linear trends. Future work should determine if these effects are more general (vs. task specific) and consider additional levels of overhead working height. Based on the present results, it is recommended that, if overhead work cannot be avoided, extreme reaches should be avoided.

Acknowledgement

The authors thank Dr. Robert T. Smith and José Banaag for their assistance in experimental design. Support for this work was provided by Honda of America MFG, Inc.

References

Allander, E., 1974, Prevalence, incidence and remission rates of some common rheumatic diseases or syndromes. *Scandinavian Journal of Rheumatology*, **3,** 145–153.

Anton, D., Shibley, L.D., Fethke, N.B., Hess, J., Cook, T.M. and Rosecrance, J., 2001, The effect of overhead drilling position on shoulder moment and electromyography. *Ergonomics*, **44,** 489–501.

Armstrong, T.J., Buckle, P., Fine, L.J., Hagberg, M., Jonsson, B., Kilbom, A., Kuorinka, I.A.A., Silverstein, B.A., Sjogaard, G. and Viikari-Juntura, E.R.A., 1993, A conceptual model for work-related neck and upper-limb musculoskeletal disorders. *Scandinavian Journal of Work, Environment and Health*, **19,** 73–84.

Arnall, F.A., Koumantakis, G.A., Oldham, J.A. and Cooper, R.G., 2002, Between-days reliability of electromyographic measures of paraspinal muscle fatigue at 40, 50 and 60% levels of maximal voluntary contractile force. *Clinical Rehabilitation*, **16,** 761–771.

Bartko, J.J., 1976, On various intraclass correlation reliability coefficients. *Psychological Bulletin*, **83,** 762–765.

Bjelle, A., Hagberg, M. and Michaelsson, G., 1979, Clinical and ergonomic factors in prolonged shoulder pain among industrial workers. *Scandinavian Journal of Work, Environment and Health*, **5,** 205–210.

Bjelle, A., Hagberg, M. and Michaelson, G., 1981, Occupational and individual factors in acute shoulder-neck disorders among industrial workers. *British Journal of Industrial Medicine*, **38,** 356–363.

Björklund, M., Crenshaw, A.G., Djupsjöbacka, M. and Johansson, H., 2000, Position sense acuity is diminished following repetitive low-intensity work to fatigue in a simulated occupational setting. *European Journal of Applied Physiology*, **81,** 361–367.

Björkstén, M.G., Boquist, B., Talbäck, M. and Edling, C., 2001, Reported neck and shoulder problems in female industrial workers: the importance of factors at work and at home. *International Journal of Industrial Ergonomics*, **27,** 159–170.

Borg, G., 1982, Psychophysical bases of perceived exertion. *Medicine & Science in Sports & Exercise*, **14,** 277–281.

Brox, J.I., 2003, Shoulder pain. *Best Practice & Research Clinical Rheumatology*, **17,** 33–56.

Carpenter, J.E., Blasier, R.B. and Pellizzon, G.G., 1998, The effects of muscle fatigue on shoulder joint position sense. *The American Journal of Sports Medicine*, **26,** 262–265.

Chaffin, D.B., 1973, Localized muscle fatigue – definition and measurement. *Journal of Occupational Medicine*, **15,** 346–354.

Dedering, Å., Németh, G. and Harms-Ringdahl, K., 1999, Correlation between electromyographic spectral changes and subjective assessment of lumbar muscle fatigue in subjects without pain from the lower back. *Clinical Biomechanics*, **14,** 103–111.

Dedering, Å., Roos, A.F., Hjelmsäter, M., Elfving, B., Harms-Ringdahl, K. and Németh, G., 2000, Between-days reliability of subjective and objective assessments of back extensor muscle fatigue in subjects without lower-back pain. *Journal of Electromyography and Kinesiology*, **10,** 151–158.

Denegar, C.R. and Ball, D.W., 1993, Assessing reliability and precision of measurement: an introduction to intraclass correlation and standard error of measurement. *Journal of Sports Rehabilitation*, **2,** 35–42.

Dennerlein, J.T., Ciriello, V.M., Kerin, K.J. and Johnson, P.W., 2003, Fatigue in the forearm resulting from low-level repetitive ulnar deviation. *American Industrial Hygiene Association Journal*, **64,** 799–805.

Dvir, Z. and Keating, J., 2001, Reproducibility and validity of a new test protocol for measuring isokinetic trunk extension strength. *Clinical Biomechanics*, **16,** 627–630.

Elfving, B., Németh, G., Arvidsson, I. and Lamontagne, M., 1999, Reliability of EMG spectral parameters in repeated measurements of back muscle fatigue. *Journal of Electromyography and Kinesiology*, **9,** 235–243.

Flatow, E.L., Soslowsky, L.J., Ticker, J.B., Pawluk, R.J., Hepler, M., Ark, J., Mow, V.C. and Bigliani, L.U., 1994, Excursion of the rotator cuff under the acromion: patterns of subacromial contact. *The American Journal of Sports Medicine*, **22,** 779–788.

Gamet, D., Duchêne, J., Bar-Garapon, C. and Goubel, F., 1993, Surface electromyogram power spectrum in human quadriceps muscle during incremental exercise. *Journal of Applied Physiology*, **74,** 2704–2710.

Garg, A., Hegmann, K.T., Schwoerer, B.J. and Kapellusch, J.M., 2002, The effect of maximum voluntary contraction on endurance times for the shoulder girdle. *International Journal of Industrial Ergonomics*, **30,** 103–113.

Gerdle, B., Eriksson, N.-E., Brundin, L. and Edström, M., 1988, Surface EMG recordings during maximum static shoulder forward flexion in different positions. *European Journal of Applied Physiology*, **57,** 415–419.

Hagberg, M., 1984, Occupational musculoskeletal stress and disorders of the neck and shoulder: a review of possible pathophysiology. *International Archives of Occupational and Environmental Health*, **53,** 269–278.

Hagberg, M. and Wegman, D.H., 1987, Prevalence rates and odds ratios of shoulder-neck diseases in different occupational groups. *British Journal of Industrial Medicine*, **44,** 602–610.

Hammarskjöld, E. and Harms-Ringdahl, K., 1992, Effect of arm-shoulder fatigue on carpenters at work. *European Journal of Applied Physiology*, **64,** 402–409.

Herberts, P. and Kadefors, R., 1976, A study of painful shoulder in welders. *Acta Orthopaedica Scandinavica*, **47,** 381–387.

Herberts, P., Kadefors, R. and Broman, H., 1980, Arm positioning in manual tasks: an electromyographic study of localized muscle fatigue. *Ergonomics*, **23,** 655–665.

Hunter, S.K. and Enoka, R.M., 2003, Changes in muscle activation can prolong the endurance time of a submaximal isometric contraction in humans. *Journal of Applied Physiology*, **94,** 108–118.

Jaric, S., Blesic, S., Milanovic, S., Radovanovic, S., Ljubisavljevic, M. and Anastasijevic, R., 1999, Changes in movement final position associated with agonist and antagonist muscle fatigue. *European Journal of Applied Physiology*, **80,** 467–471.

Järvholm, U., Palmerud, G., Karlsson, D., Herberts, P. and Kadefors, R., 1991, Intramuscular pressure and electromyography in four shoulder muscles. *Journal of Orthopaedic Research*, **9,** 609–619.

Järvholm, U., Palmerud, G., Styf, J., Herberts, P. and Kadefors, R., 1988a, Intramuscular pressure in the supraspinatus muscle. *Journal of Orthopaedic Research*, **6,** 230–238.

Järvholm, U., Styf, J., Suurkula, M. and Herberts, P., 1988b, Intramuscular pressure and muscle blood flow in supraspinatus. *European Journal of Applied Physiology*, **58,** 219–224.

Keppel, G., 1991, *Design and Analysis: A Researcher's Handbook* (Upper Saddle River, NJ: Prentice Hall).

Kilbom, Å., Persson, J. and Jonsson, B.G., 1986, Disorders of the cervicobrachial region among female workers in the electronics industry. *International Journal of Industrial Ergonomics*, **1,** 37–47.

Kourinka, I. and Koskinen, P., 1979, Occupational rheumatic diseases and upper limb strain in manual jobs in a light mechanical industry. *Scandinavian Journal of Work, Environment and Health*, Suppl., **3,** 39–47.

Larivière, C., Arsenault, A.B., Gravel, D., Gagnon, D. and Loisel, P., 2002, Evaluation of measurement strategies to increase the reliability of EMG indices to assess back muscle fatigue and recovery. *Journal of Electromyography and Kinesiology*, **12,** 91–102.

Larsson, B., Karlberg, C., Elert, J. and Gerdle, B., 1999, Reproducibility of surface EMG during dynamic shoulder forward flexions: a study of clinically healthy subjects. *Clinical Physiology*, **19,** 433–439.

Lohr, J.R. and Uhthoff, H.K., 1990, The microvascular pattern of the supraspinatus tendon. *Clinical Orthopaedics and Related Research*, **254,** 35–38.

Madeleine, P., Lundager, B., Voigt, M. and Arendt-Nielsen, L., 1998, Sensory manifestations in experimental and work-related chronic neck-shoulder pain. *European Journal of Pain*, **2,** 251–260.

Maeda, K., 1977, Occupational cervicobrachial disorder and its causative factors. *Journal of Human Ergology*, **6,** 193–202.

Nagata, S., Arsenault, A.B., Gagnon, D., Smyth, G. and Mathieu, P.-A., 1990, EMG power spectrum as a measure of muscular fatigue at different levels of contraction. *Medical & Biological Engineering & Computing*, **28,** 374–378.

Nargol, A.V.F., Jones, A.P.C., Kelly, P.J. and Greenough, C.G., 1999, Factors in the reproducibility of electromyographic power spectrum analysis of lumbar paraspinal muscle fatigue. *Spine*, **24,** 883–888.

National Institute for Occupational Safety and Health, 1997, *Musculoskeletal Disorders and Workplace Factors. A Critical Review of Epidemiologic Evidence for Work-Related Musculoskeletal Disorders of the Neck, Upper Extremity and Low Back*, DHHS (NIOSH) publication, pp. 97–141 (Cincinnati: National Institute for Occupational Safety and Health).

Nussbaum, M.A., 2001, Static and dynamic myoelectric measures of shoulder muscle fatigue during intermittent dynamic exertions of low to moderate intensity. *European Journal of Applied Physiology*, **85,** 299–309.

Nussbaum, M.A., Clark, L.L., Lanza, M.A. and Rice, K.M., 2001, Fatigue and endurance limits during intermittent overhead work. *American Industrial Hygiene Association Journal*, **62,** 446–456.

Öberg, T., Sandsjö, L. and Kadefors, R., 1994, Subjective and objective evaluation of shoulder muscle fatigue. *Ergonomics*, **37,** 1323–1333.

Ohlsson, K., Attewell, R.G., Pålsson, B., Karlsson, B., Balogh, I., Johnsson, B., Ahim, A. and Skerfving, S., 1995, Repetitive industrial work and neck and upper limb disorders in females. *American Journal of Industrial Medicine*, **27,** 731–747.

Punnett, L., Fine, L.J., Keyserling, W.M., Herrin, G.D. and Chaffin, D.B., 2000, Shoulder disorders and postural stress in automobile assembly work. *Scandinavian Journal of Work, Environment and Health*, **26,** 283–291.

Putz-Anderson, V. and Galinsky, T.L., 1993, Psychophysically determined work durations for limiting shoulder girdle fatigue from elevated manual work. *International Journal of Industrial Ergonomics*, **11,** 19–28.

Rainoldi, A., Bullock-Saxton, J.E., Cavarretta, F. and Hogan, N., 2001, Repeatability of maximal voluntary force and of surface EMG variables during voluntary isometric contraction of quadriceps muscles in healthy subjects. *Journal of Electromyography and Kinesiology*, **11,** 425–438.

Rohmert, W., 1960, Ermittlung von Erholungspausen für statische Arbeit des Menschen. *Internationale Zeitschrift für Angewandte Physiologie einschliesslich Arbeitsphysiologie* **18,** 123–164.

Sakakibara, H., Miyao, M., Kondo, T. and Yamada, S., 1995, Overhead work and shoulder-neck pain in orchard farmers harvesting pears and apples. *Ergonomics*, **38,** 700–706.

Sejersted, O.M. and Vøllestad, N.K., 1993, Chapter 3: Physiology of muscle fatigue and associated pain. In *Progress in Fibromyalgia and Myofascial Pain*, H. Værøy and H. Merskey (Eds.), pp. 41–51 (Amsterdam: Elsevier Science Publishers, BV).

Shrout, P.E. and Fleiss, J.L., 1979, Intraclass correlations: uses in assessing rater reliability. *Psychological Bulletin*, **86,** 420–428.

Sleivert, G.G. and Wenger, H.A., 1994, Reliability of measuring isometric and isokinetic peak torque, rate of torque development, integrated electromyography and tibial nerve conduction velocity. *Archives of Physical Medicine and Rehabilitation*, **75,** 1315–1321.

Sommerich, C.M. and Hughes, R.E., 2006, Aetiology of work-related disorders of the rotator cuff tendons: research and theory. *Theoretical Issues in Ergonomics Science*, **7,** 19–38.

Sommerich, C.M., McGlothlin, J.D. and Marras, W.S., 1993, Occupational risk factors associated with soft tissue disorders of the shoulder: a review of recent investigations in the literature. *Ergonomics*, **36,** 697–717.

Sporrong, H., Palmerud, G., Kadefors, R. and Herberts, P., 1998, The effect of light manual precision work on shoulder muscles – an EMG analysis. *Journal of Electromyography and Kinesiology*, **8,** 177–184.

Stokdijk, M., Biegstraaten, M., Ormel, W., de Boer, Y.A., Veeger, H.E.J. and Rozing, P.M., 2000, Determining the optimal flexion-extension axis of the elbow in vivo – a study of interobserver and intraobserver reliability. *Journal of Biomechanics*, **33,** 1139–1145.

Svendsen, S.W., Bonde, J.P., Mathiassen, S.E., Stengaard-Pedersen, K. and Frich, L.H., 2004a, Work related shoulder disorders: quantitative exposure-response relationships with reference to arm posture. *Occupational and Environmental Medicine*, **61,** 844–853.

Svendsen, S.W., Gelineck, J., Mathiassen, S.E., Bonde, J.P., Frich, L.H., Stengaard-Pedersen, K. and Egund, N., 2004b, Work above shoulder level and degenerative alterations of the rotator cuff tendons. *Arthritis & Rheumatism*, **50,** 3314–3322.

Ulin, S.S., Ways, C.M., Armstrong, T.J. and Snook, S.H., 1990, Perceived exertion and discomfort versus work height with a pistol-shaped screwdriver. *American Industrial Hygiene Association Journal*, **21,** 588–594.

Wiker, S.F., Chaffin, D.B. and Langolf, G.D., 1989, Shoulder posture and localized muscle fatigue and discomfort. *Ergonomics*, **32,** 211–237.