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Quantifying repetitive hand activity for epidemiological research on musculoskeletal disorders – Part I: individual exposure assessment

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An exposure measurement approach is described for quantifying repetitive hand activity of individual workers in a prospective epidemiological study on work-related upper extremity musculoskeletal disorders. A total of 733 subjects were involved in this study at the baseline. Hand activities were quantified by force and repetition. Force levels were measured by workers' self-reports, ergonomists' estimates based on observation and measurements with instrumentation. Repetition levels were measured by detailed time–motion analyses using two repetitive hand activity definitions and ergonomists' estimates using scales for the American Conference of Governmental Industrial Hygienists hand activity level and the Strain Index. Results showed that the present exposure assessment approach seems to be able to quantify force level and repetitiveness of hand activities. Repetitive hand activity is quantified differently depending on whether forceful hand exertion or repetitive muscle activity is used as the definition. These hand activity definitions may quantify different physical exposure phenomena. Individual exposure assessment is important in epidemiological research of musculoskeletal disorders as there are interactions between the individual subjects and the measured parameters. These interactions may vary between exposure parameters.

Keywords: Individual exposure quantification; Observational; Self-reporting; Direct measurement; Repetition; Hand force

1. Introduction

Repetitive hand activity has been associated with symptoms and disorders in the upper extremities (Silverstein *et al.* 1986, 1987a,b, Latko *et al.* 1999). For instance, using an

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observational method, Burdorf *et al.* (1997) found that forceful exertions over 100 N were related to elbow pain and wrist pain. Silverstein *et al.* (1987a) studied 652 workers in 39 jobs in seven different plants and found that the odds ratio for carpal tunnel syndrome in highly repetitive jobs compared to low repetition jobs, irrespective of force, was 5.5 ($p < 0.05$). The odds ratio increased to 15.5 ($p < 0.05$) for jobs with combined exposures to high force and high repetition when compared to jobs with low force and low repetition.

Several large prospective epidemiological studies have been conducted recently to define relationships between various exposure factors and musculoskeletal disorders (Punnett *et al.* 2000, Fallentin *et al.* 2001, Leclerc *et al.* 2001). Quantifying the various exposure parameters, including repetitive hand activities, has been one of the major research topics in these studies.

The use of group exposure profiling methods has been a common practice in many occupational health epidemiological studies, including work-related musculoskeletal disorders research (e.g. Bovenzi *et al.* 1994, Fallentin *et al.* 2001). Using the group exposure profiling approach, exposure parameters are measured in a sample of subjects within each occupational group. Usually arithmetic means are calculated and used as the exposures for everybody in the same occupational group. Some researchers use the group exposure profiling approach at task level (task-based approach) and calculate an individual worker's job exposure by considering the individual's task distribution over a typical work shift (e.g. Jansen *et al.* 2004). Recent studies show that the task-based approach can be very imprecise and only marginally better than estimates based on jobs of the same occupation (Svendsen *et al.* 2005). A job-based approach is suggested in many cases (Svendsen *et al.* 2005). The group-based exposure quantification strategy, either task-based or job-based, is based on the homogeneity assumption that workers in the same exposure group have similar exposure profiles when they perform the same tasks or the same jobs. This assumption, however, is not often fulfilled in the physical exposure parameters of musculoskeletal disorders research. For example, workers may work on exactly the same job, using the same type of tool on the same type of product. However, they may have very different exposure profiles (posture, force and repetitive motions) due to differences in work techniques, location on the production line, workers' anthropometric differences and other factors. Fallentin *et al.* (2001) found larger within-group variance than between-group variance for some exposure parameters, despite efforts to optimize the group homogeneity. Consequently, individual exposure quantification appears to be necessary in epidemiological research into factors associated with musculoskeletal disorders. Unfortunately, due to the large resource requirements of individual exposure assessment, few studies have been able to be conducted using this type approach of exposure measurement.

Moore *et al.* (1991) described underlying mechanisms of repetitive hand activities consistent with the epidemiological findings. These underlying mechanisms include the forces of tendons on the median nerve and the synovial sheath, movement of the tendon with regard to the tendon sheath, friction between the tendon and the tendon sheath, strain in the tendons, and muscle fatigue and overuse. Ergonomic exposure assessment methods in epidemiological studies have been seeking surrogate measures for these hypothesized mechanisms. For instance, repetitive hand activity has been assessed through the quantification of exertion of forces, repetition of wrist movements and/or muscle contractions of the hand and forearm, while considering hand posture and exposure duration (American Conference of Governmental Industrial Hygienists 2001). Operationally, repetitive hand activity has been quantified in several different ways. The primary differences between studies have been in the definitions and the measurement methods used. For example, repetitive hand activity has been defined according to external forces (Stetson *et al.* 1991), hand/wrist movements (Fallentin *et al.* 2001), the repetitive use of the hand (Keyserling *et al.* 1993) and forearm muscle activities (Cook *et al.* 1998). Measurement methods have included self-reporting, on-site/off-site observations and direct measurement.

Jobs with a basic cycle time of 30 s or less and/or jobs in which over 50% of the work cycle involves similar upper extremity motion patterns have been considered as repetitive (Silverstein *et al.* 1987a, Keyserling *et al.* 1993). Checklists have been used by ergonomists during worksite visits to record repetitive use of the hand and dichotomous force levels. In some studies (e.g. Harber *et al.* 1994, Punnett *et al.* 2004), repetition and force levels have also been rated by workers' self-reports.

Stetson *et al.* (1991) defined hand force exertions as conspicuous applications of force by the hand and included using the hand to hold, manipulate, trigger, push, pull or otherwise handle an object. Using the same definition, Latko (1997) and Latko *et al.* (1997) developed an observational method using a series of 10-cm visual analogue scales, with verbal anchors and benchmark examples, to quantify the level of hand force and repetition of hand activity separately. The rating scale for repetition reflected both the dynamic aspect of hand movements and the amount of hand recovery or idle time.

Fallentin *et al.* (2001) conducted observations of video-taped tasks in a large prospective study. Repetitiveness of hand activity was quantified by the number of movements of the joints in a unit time. The researchers used the methods–time measurement system (Niebel 1988) to describe a movement in the analysis. Force levels were estimated using a 5-point ordinal scale with verbal anchoring (Moore and Garg 1995). This study categorized exposure through measurements of workers at a group level.

Amplitude and repetitive characteristics of the forearm muscle activity, as quantified by surface electromyography (EMG), has been used to evaluate repetitive hand activities (Cook *et al.* 1998, Bao *et al.* 2001). Radwin *et al.* (1994) developed a frequency domain approach for averaging elemental data recorded for repetitive cycles. Parameters for a frequency-weighted filter were developed using psychophysical data for equivalent discomfort levels, resulting from repetitive movements of different amplitudes and frequencies. Examining EMG signals in the amplitude and time domains in order to quantify physical exposure has also been used in other muscles of the upper extremities (Mathiassen and Winkel 1991, Bao *et al.* 1996).

This paper presents an individual exposure assessment approach developed as a part of a large prospective epidemiological study of work-related upper extremity musculoskeletal disorders (UEMSDs). The overall objective of the study was to assess the incidence and persistence of UEMSDs as a function of an individual, physical load and psychosocial factors. The specific aim of this paper is to introduce the individual exposure assessment approach used for the baseline measurements in the prospective study. Several different methods were used to quantify hand repetitiveness and hand forces across subjects. A companion paper (Bao *et al.* 2006) presents the comparisons between the different measurement methods.

2. Method

2.1. *Subjects*

Exposure parameters and health outcomes were individually measured from 733 subjects at 12 different worksites in manufacturing and health care sectors (table 1). A total of 350

Table 1. Distribution of subjects according to industry sector and to initial exposure category based on on-site walk-through observation.

Force	High			Low			
Repetition	High	Medium	Low	High	Medium	Low	Total
Manufacturing n (%)	55 (7.5)	104 (14.2)	44 (6.0)	49 (6.7)	259 (35.3)	123 (16.8)	634 (86.5)
Health care n (%)	1 (0.1)	10 (1.4)	2 (0.3)	4 (0.6)	31 (4.2)	51 (7.0)	99 (13.5)
Total n (%)	56 (7.6)	114 (15.6)	46 (6.3)	53 (7.2)	290 (39.6)	174 (23.7)	733 (100.0)
Age (years)							
Median	35.8	36.5	39.9	40.4	41.4	39.0	39.9
Range	(18.1–63.1)	(19.1–64.6)	(19.9–58.7)	(18.1–63.4)	(18.1–64.9)	(19.5–64.1)	(18.1–64.9)

n = number of subjects; % = percentage of the total subjects.

women (median age 42.0 years; range 18.1–64.1 years) and 383 men (median age 36.6 years; range 18.1–64.9 years) participated. In order to ensure that there was sufficient variation in the exposure among the subjects at each worksite, potential subjects were invited to volunteer from jobs of varied exposures, identified through a job categorization process. Based on site walk-through, jobs at each site were initially categorized into one of six exposure categories according to a combination of hand force (two levels: low (LF) and high (HF)) and repetition (three levels: low (LR), medium (MR) and high (HR)) using scales from Latko (1997). Efforts were attempted to recruit a similar number of subjects in each exposure category (table 1), although such efforts were not always successful. The job categorization was subjectively determined by an ergonomist through brief observations of workers in jobs at each worksite. The job categorization was not used as a measurement of exposure in this study.

This study was approved by the Washington State Institutional Review Board. Written consent from each subject was obtained prior to the data collection.

2.2. *Data collection*

During worksite visits each worker was video-taped performing his/her job for a minimum of 15 min, depending on the type of job. Cyclic single task jobs were filmed for 15 min and cyclic four-task jobs were filmed for 40 min (10 min for each task). For a non-cyclic single task job, three 5-min samples were recorded at randomly selected periods during the shift. This was aimed at reducing the temporal component of exposure variability within individual workers. Two synchronized video cameras were used in order to capture both body sides of a subject during task performance. The recorded video was used for later analysis in the laboratory. Task activities were observed and documented by ergonomists during the video-taping period in order to obtain hand repetitiveness and hand force estimates.

Repetitive hand activity was measured in two dimensions, repetitiveness and force. Several different methods were used to quantify the repetitiveness and force. Table 2 presents a list of the different variables for each of the dimensions. Repetitiveness of hand activity was analysed using two different definitions: one based on forceful hand exertion and the other based on repetitive hand muscle activity (referred to as 'repetitive muscle activity' in the following text).

Forceful hand exertion was determined subjectively by ergonomists during on-site observation. The definition 'forceful hand exertion' was similar to that used by Stetson *et al.* (1991), where it was defined as 'a conspicuous application of force by the hand and included using the hand to hold, manipulate, trigger, push, pull, or otherwise handle an object'. Operationally, force data were collected if force was obvious and considered of importance by an ergonomist. Conceptually, a forceful hand exertion was defined as a lifting force of $\geq$8.9 N, a push/pull force of $\geq$44.5 N, a pinch grip force of $\geq$8.9 N or a power grip force of $\geq$44.5 N. These cut-off values were chosen for consistency with Stetson *et al.* (1991) and hand force limits used in the repealed Washington State Ergonomics Rule (Washington State Department of Labor and Industries 2000). The actual force value was not known until measured; therefore, in practice, forces that were lower than the defined levels were occasionally measured. Lifting forces were quantified by measuring the object weight. Push/pull forces were measured using a force gauge and are combined as a single force type, although it is recognized that they may have different physiological effects. A pinch or a power grip force was measured using a force matching method (Bao and Silverstein 2005). This was done by asking the subject to

Table 2. List of variables quantifying repetitiveness and force of hand activity.

	Variable	Explanation
Repetitiveness	• Forceful hand exertion (frequency and duty cycle)	Based on definition of forceful hand exertion* and obtained through detailed time study of recorded task performance.
	• Repetitive muscle activity (frequency and duty cycle)	Based on definition of repetitive muscle activity† and obtained through detailed time study on recorded task performance.
	• Hand activity level	Estimated by ergonomists on-site, based on a scale suggested by American Conference of Governmental Industrial Hygienists (2001)
	• Duration of exertion • Efforts per min • Speed of work	Estimated by ergonomists on-site using the original 5-point scale from the Strain Index (Moore and Garg 1995)
Force	• Lifting and push/pull forces (N)	Forces directly measured using a force gauge
	• Pinch and power grip forces (N)	Forces estimated using a force matching method (Bao and Silverstein 2005)
	• Lifting, push/pull, pinch and power grip forces rated on a scale of 0–10	Forces estimated by ergonomists on-site using a scale of 0–10 (Latko 1997b)
	• Pinch and power grip forces rated on a scale of 0–10	Hand forces self-reported by subjects on-site using the Borg 10-point rating of perceived exertion scale (Borg 1982)

*A 'forceful hand exertion' is defined as a lifting force of ≥ 8.9 N, a push/pull force of ≥ 44.5 N, a pinch grip force of ≥ 8.9 N or a power grip force of ≥ 44.5 N.
†'Repetitive muscle activity' is defined as all 'required' hand and forearm muscle efforts during task performance.

replicate on a force dynamometer the hand force that he/she used in the task, using similar hand/wrist postures. This process was repeated three times and the median of the three grip forces was used in the analyses.

Ergonomists also estimated forces using a 10-point scale (0 = no force; 1 = low force level; 10 = high force level) based on the American Conference of Governmental Industrial Hygienists (ACGIH) documentation on hand activity level (HAL) Threshhold Limit Values (TLV), which is adapted from Latko *et al.* (1997). This estimation was applied to all force types (lifting, push/pull, pinch grip and power grip). Subjects also rated the force level of pinch grip and power grip forces using a 10-point Borg rating of perceived exertion scale (Borg 1982). Subjects did not rate lifting and push/pull forces.

2.3. *Data processing and analysis*

The video tapes were digitized and processed in the laboratory. A detailed time-study was conducted for each of the measured forceful hand exertions using the Multi-Video Task Analysis (MVTA) program (Yen and Radwin 1995). Subjects were randomly assigned to one of three ergonomists involved in this project. The analysis was done by the ergonomist who collected the data on-site and, consequently, was familiar with the task performance and the forceful hand exertion definitions in the specific task. This detailed time–motion analysis involved reviews of the recorded video clips, often in slow motion mode when the task performance was fast. Time marks were inserted at the start and end of each of the forceful hand exertions. The analysis was done for the left and right hands separately.

Percent time (%) and frequency of each type of forceful hand exertion were computed. For each force type, the time-weighted average force level was calculated at the task level according to the duration of forces at different amplitudes. Using task distribution information (number of tasks in each job and hours spent on each task) that was collected during the worksite visits on each individual worker, the time-weighted average force level for each force type was calculated at the job level. The frequency of the repetitive forceful hand exertion and average duty cycle (% cycle in exertion) were calculated using occurrences of all types of forceful hand exertions. The activities were considered mutually exclusive. For example, if hand power grip force happened during lifting, only one force would be counted in the frequency calculation.

The second definition of repetitive hand activity, repetitive muscle activity, included all hand muscle activities. In this definition all 'required' hand and forearm muscle efforts were considered as a hand exertion activity, regardless of the force required; for example, moving a piece of paper from one location to another would count as a hand exertion activity. 'Required' efforts were defined as any action that was required by the job rather than the personal preference of the worker. A worker holding a piece of paper and talking to a co-worker would not be considered a hand exertion activity when the piece of paper had no relation to the communication.

Repetitive muscle activity was also quantified using time–motion video analysis. Using the hand activity definition, the same video clips were analysed utilizing the MVTA program (Yen and Radwin 1995). These analyses were processed by laboratory technicians who did not have prior knowledge of ergonomics and experience in such analysis. Training specific to the analysis was provided by ergonomists. Laboratory technicians were used to do the analysis rather than ergonomists for two reasons. First, the definition of the repetitive muscle activity was relatively simple compared to the forceful exertion analysis. Second, resources required to perform this analysis were enormous. In the analysis, time-marks were inserted when a defined hand activity (repetitive muscle activity) occurred or stopped, based on the technicians' subjective judgement. The laboratory technicians adjusted the speed of the video playback in order to best observe hand exertion activities. Analysis for repetitive muscle activity was done on randomly selected 1-min video intervals. The number of intervals selected for the analysis depended on the number of tasks in the job. For a single-task job, five randomly selected intervals were used. For a two-task job, six (two tasks × three intervals) were analysed. For a three- or four-task job, six (three tasks × two intervals) or eight (four tasks × two intervals) were analysed, respectively.

To minimize possible between-analyst variation, each subject's job was analysed by two technicians. Each technician analysed approximately half of the video intervals. The six technicians involved in the analysis were randomly paired to each subject to eliminate possible systematic analyst variation.

The frequency of exertion and duty cycle was calculated for each 1-min analysed video interval. This allowed for calculations of within-task variation and between-analyst variation. Corresponding variables for the task level were computed by averaging the results from all video intervals. At the individual's job level, corresponding variables were computed using a time-weighted average according to the task distribution information collected during worksite visits.

Repetitive hand activity was also estimated subjectively by the ergonomists during worksite visits. Two standards were used. The first was the ACGIH's HAL scale (American Conference of Governmental Industrial Hygienists 2001), which uses verbal anchors on a scale for observer estimation (e.g. 0 = hand idle most of the time, no regular exertions; 10 = rapid, steady motions/difficulty keeping up or continuous exertion). The second subjective estimation included three elements from the Strain Index method: (1) duration of exertion (% of cycle); (2) efforts per min; (3) speed of work (Moore and Garg 1995). These measurements were made using the original 5-point scale from the Strain Index method (Moore and Garg 1995). All subjective estimates were made at the task level and then, based on the task distribution information of the individual's job, time-weighted to obtain corresponding parameters at the individual's job level. This is a modified application of the HAL and Strain Index methods, as both methods were originally designed for only mono-task jobs.

2.4. *Statistical analysis*

Descriptive statistics were calculated for force amplitude by type of force application at the individual's job level and by the original walk-through exposure category. The individual exposure parameters were summarized by the initial walk-through exposure category. Similar calculations were also made for the time–motion video analysis results of hand activity frequencies and duty cycles based on the two repetitive hand activity definitions and the subjectively estimated parameters (HAL and the three Strain Index parameters). For subjects in each exposure category, the standard deviations were calculated for these variables to indicate variation within groups. One-way ANOVA was performed to test differences between the six different exposure categories. The paired Student t-test was used to compare data between the left and right hands. A significance level of 0.05 was used for all statistical comparisons.

Inter-subject coefficients of variation (CV) were calculated for the various exposure parameters within each exposure category as indicators of within-group exposure variation or group homogeneity. This value reflects dispersion of data around the mean of a single dataset and is calculated from the standard deviation divided by the mean. A single number estimate (Q-value) of within-group and between-group variance for the different exposure variables was obtained by computing the ratio of the mean of the standard deviations for all exposure groups (within-group standard deviation) to the standard deviation of the mean values across exposure groups (between-group standard deviation) (Fallentin *et al.* 2001).

All analyses were performed using the SAS program (version 9; SAS Institute, Inc., Cary, NC, USA).

3. Results

3.1. *Force levels of different exposure categories*

A total of 1851 forceful exertion measurements were taken from the 733 subjects at the baseline. The main forceful exertion exposure was lifting (47.7%). Pinch grip hand forces were seen more often than power grip hand forces. Almost 9% of the measurements taken were lower than the conceptually defined forceful exertion levels.

Large between-group variation in the directly measured or 'force matched' measurements (lifting, pushing/pulling, pinch gripping and power gripping) was found between the different exposure categories (as seen in figure 1, where only right hand forces are shown, $p < 0.05$). Even within each exposure category, there was large within-group variance in the force levels, as seen from the wide 95% CI (figure 1). Average CVs for the various force measures ranged between 1.24 (lifting force of the right hand) and 3.12 (push/pull force of the left hand). This showed again the large variance within each exposure category for the various force measurements. The Q-values (table 3) ranged

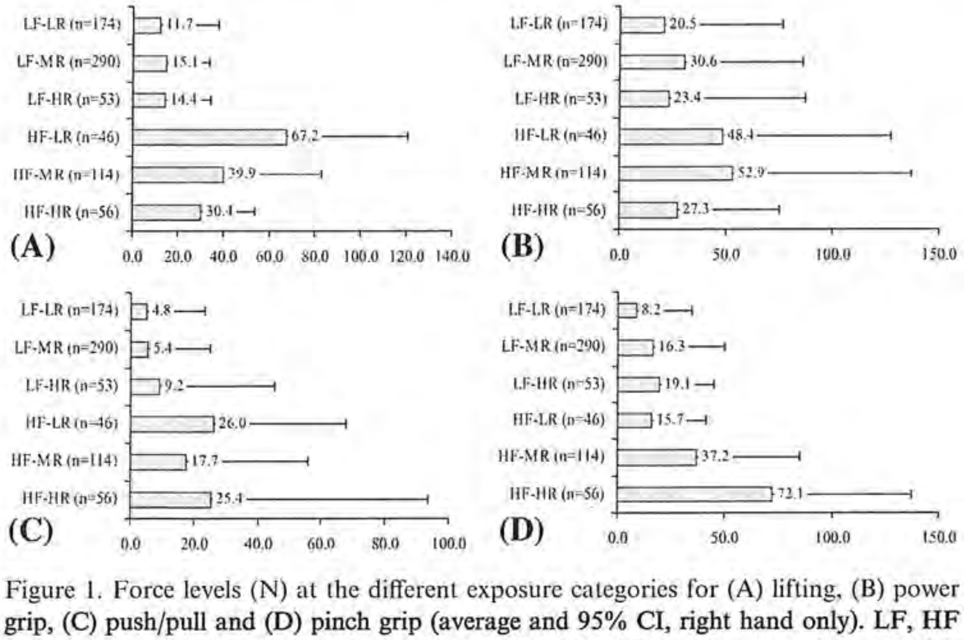

Figure 1. Force levels (N) at the different exposure categories for (A) lifting, (B) power grip, (C) push/pull and (D) pinch grip (average and 95% CI, right hand only). LF, HF represent low and high force respectively; LR, MR, HR represent low, medium and high repetition respectively.

Table 3. Average forces (N) of right and left hands by exposure category.

	Job exposure category‡	Right hand Mean (SD)	Left hand Mean (SD)	Difference†	*p*-value
Lifting (N)	HF-HR (n = 56)	30.4 (23.1)	31.9 (27.7)	−1.5	0.3022
	HF-MR (n = 114)	39.9 (43.1)	39.3 (42.5)	0.6	0.4540
	HF-LR (n = 46)	67.2 (53.6)	68.8 (53.8)	−1.6	0.3363
	LF-HR (n = 53)	14.4 (19.7)	13.8 (19.2)	0.6	0.1512
	LF-MR (n = 290)	15.1 (18.8)	15.3 (19.2)	−0.20	0.6241
	LF-LR (n = 174)	11.7 (25.7)	11.2 (24.1)	0.5	0.2792
	Q-value	1.44	1.41		
Push/pull (N)	HF-HR (n = 56)	25.4 (68.0)	22.3 (63.4)	3.1	0.2160
	HF-MR (n = 114)	17.7 (37.9)	14.9 (28.7)	2.8	0.2009
	HF-LR (n = 46)	26.0 (41.5)	22.5 (33.1)	3.5	0.2252
	LF-HR (n = 53)	9.2 (35.9)	13.2 (61.8)	−4.0	0.2791
	LF-MR (n = 290)	5.4 (19.4)	5.5 (20.3)	−0.1	0.8695
	LF-LR (n = 174)	4.8 (18.5)	4.7 (19.4)	0.1	0.7505
	Q-value	3.81	4.85		
Pinch grip (N)	HF-HR (n = 56)	72.1 (65.2)	71.2 (65.8)	0.9	0.2744
	HF-MR (n = 114)	37.2 (48.0)	37.4 (48.1)	−0.2	0.7770
	HF-LR (n = 46)	15.7 (25.8)	15.1 (25.7)	0.6	0.2192
	LF-HR (n = 53)	19.1 (25.9)	19.1 (26.3)	0.0	0.9907
	LF-MR (n = 290)	16.3 (33.4)	13.2 (29.9)	3.1	0.0041*
	LF-LR (n = 174)	8.2 (26.3)	6.8 (25.1)	1.4	0.0371*
	Q-value	1.59	1.54		
Power grip (N)	HF-HR (n = 56)	27.3 (47.8)	16.4 (37.7)	10.9	0.0308*
	HF-MR (n = 114)	52.9 (84.5)	26.1 (70.9)	26.7	<0.0001*
	HF-LR (n = 46)	48.4 (79.2)	41.6 (78.8)	6.8	0.1069
	LF-HR (n = 53)	23.4 (63.8)	14.2 (52.0)	9.2	0.0854
	LF-MR (n = 290)	30.6 (55.5)	17.1 (46.8)	13.5	<0.0001*
	LF-LR (n = 174)	20.5 (55.8)	9.3 (41.8)	11.2	0.0004*
	Q-value	4.75	4.72		

*Significant difference at $p<0.05$.
†Difference = right hand force − left hand force.
‡A combination of hand force (two levels: low (LF); high (HF)) and repetition (three levels: low (LR); medium (MR); high (HR)).
Q-value = ratio of within-group standard deviation to between-group standard deviation (Fallentin *et al.* 2001).

between 1.41 (lifting force of the left hand) and 4.85 (push/pull force of the left hand). This indicated larger within-group variance than between-group variance. In general, for high hand force exposure category jobs, at least one of the lifting, pinch gripping or power gripping forces was high.

Similar average force distribution patterns were found for both left and right hands. However, force levels varied between the left and right hands depending on the force type and exposure category (table 3). In general, power grip hand force was greater on the right hand compared to the left ($p>0.05$). There were no significant differences between the left and right hands for lifting force levels or pushing/pulling force levels in any exposure category. No obvious differences were found between the left and right hands for the pinch grip force except in certain exposure categories.

Force levels estimated by ergonomists showed patterns similar to those in the direct force measurements and 'force matched' measurements, with some slight differences in the relationship of the relative levels between the different exposure categories. For instance, the lifting force level was higher in the HF-MR exposure category than in the HF-HR exposure category when lifting force was measured. That relationship was reversed when the lifting force was estimated by ergonomists. Overall, large variations existed between the exposure categories and within each exposure category ($p<0.05$). Average CVs for the various force estimates ranged between 0.93 (estimated lifting force of right hand) and 2.84 (estimated power grip hand force of the left hand). The Q-values ranged between 1.24 (lifting force of the left hand) and 3.77 (power grip hand force of the right hand), again indicating larger within-group variance than between-group variance.

Self-reported power grip and pinch grip hand force levels also showed patterns similar to those obtained by the other two methods, with slight differences in the relationship of the relative levels between the different exposure categories. Large variations also existed between the exposure categories ($p<0.05$) and within each exposure category when hand force was reported by subjects. Average CVs for the two reported hand forces ranged between 1.62 (pinch grip hand force of the right hand) and 2.91 (power grip hand force of the left hand). The Q-values ranged between 1.99 (pinch grip hand force of the left hand) and 4.37 (power grip hand force of the right hand), indicating larger within-group variance than between-group variance as well.

3.2. *Repetitiveness of different exposure categories*

Frequency and duty cycle of forceful hand exertion and repetitive muscle activity of the right hand are shown in figures 2 and 3. Significant variation existed between the different exposure categories ($p<0.05$). Higher frequencies of both forceful hand exertion and repetitive muscle activity were found to be associated with the higher repetition exposure categories ($p<0.05$). Higher frequencies of forceful hand exertion were also related to the high force exposure category ($p<0.05$). The relationship between frequency of repetitive muscle activity and high and low force exposure categories did not achieve statistical significance ($p>0.05$). Similar relationships were also found for duty cycles of forceful hand exertion (figure 3). Higher duty cycles of forceful hand exertion were related to both higher repetition exposure categories ($p<0.05$) and the high force exposure category ($p<0.05$). No such patterns were found between duty cycles of repetitive muscle activity and exposure categories (figure 3).

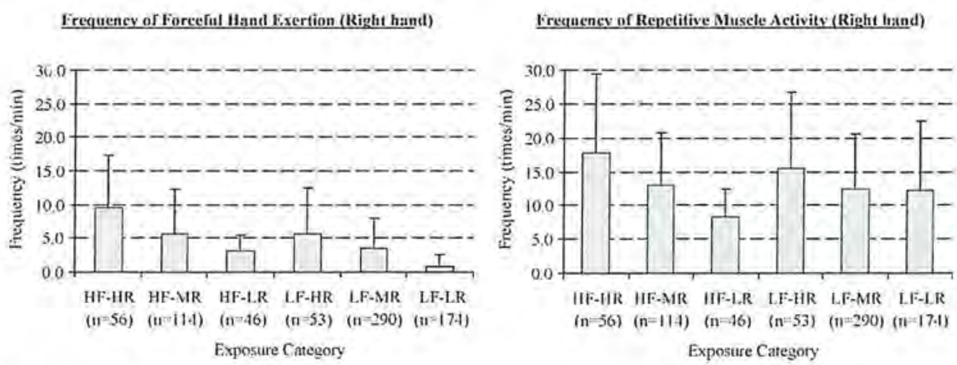

Figure 2. Frequency of forceful hand exertions and repetitive muscle activity in the different exposure categories (average and standard deviation, right hand only). LF, HF represent low and high force respectively; LR, MR, HR represent low, medium and high repetition respectively.

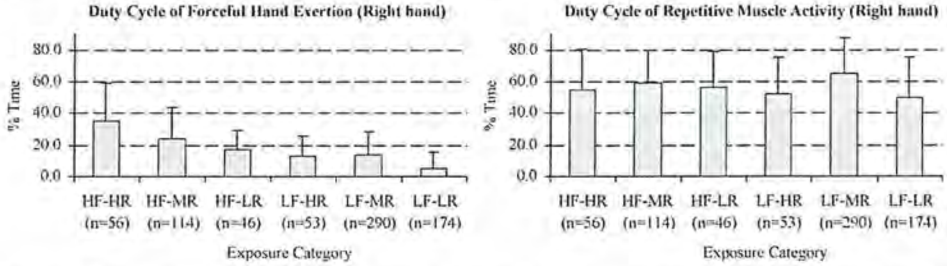

Figure 3. Duty cycle of forceful hand exertions and repetitive muscle activity in the different exposure categories (average and standard deviation, right hand only). LF, HF represent low and high force respectively; LR, MR, HR represent low, medium and high repetition respectively.

Large variation in frequency and duty cycle measurements of both hand activity measurements also existed within exposure categories. This was indicated by the large standard deviations (figures 2 and 3), as well as large CVs and Q-values. Large average CVs (1.08 to 1.31) and Q-values (1.40 to 1.65) were found for the frequency and duty cycle measurements of the forceful hand exertion. Although the average CVs for the frequency and duty cycle measurements of the repetitive muscle activity were moderate (ranging from 0.42 to 0.66), the Q-values were still quite large (ranging from 1.98 to 4.37), indicating larger within-group variance than between-group variance.

Frequency and duty cycle of forceful hand exertion and repetitive muscle activity for the right and left hands had similar distribution patterns across the different exposure categories (table 4). However, right hand forceful exertion frequencies were significantly higher compared to those of the left hand ($p<0.05$, except for the HF-HR job exposure category where the p-value was 0.07). The frequency differences between hands ranged from 0.2 to 0.7 times/min. Longer exertions, of about 4% higher on average, were found in the right hand compared to the left hand in the forceful hand exertion analysis ($p<0.05$, except for the high repetition exposure categories, where $p\approx 0.06$). Such differences between the right and left hand were not obvious for the repetitive muscle activity analysis (table 4). Right and left hand repetitive muscle activity frequencies were often not significantly different ($p>0.05$) except for jobs in the LF-LR category, where the right hand had significantly higher repetitive muscle activity frequency than the left (4.0 times/min, $p<0.0001$). However, as a general trend, the duty cycles of the repetitive muscle activity were almost 5% higher for the right hand than for the left hand (p-values ranged between <0.0001 and 0.1374).

The ergonomist's estimated measures (HAL and the three Strain Index parameters) appear to have distribution patterns similar to those of the frequencies of forceful hand exertions and repetitive muscle activity (as seen in figure 4, which shows the right hand only). Large Q-values were found for all the estimated measurements, indicating relatively large within-group variance compared to between-group variance. However, the average CVs were moderate (ranging between 0.20 and 0.38).

Estimated parameters for the right hand were usually slightly higher than those for the left hand (table 5). The differences were much less for the speed of work parameter, an estimate of the perceived speed of the work pace. Although the general trend was that right hand values were higher than those for the left hand, the significance levels varied

Table 4. Average frequency and duty cycle of forceful hand exertion† and repetitive muscle activity‡ for the right and left hands by exposure category.

	Job exposure category§	Right hand Mean (SD)	Left hand Mean (SD)	Difference¶	p-value
Frequency of forceful hand exertion (times/min)	HF-HR (n = 56)	9.6 (7.7)	8.9 (7.5)	0.7	0.0740
	HF-MR (n = 114)	5.6 (6.6)	4.9 (6.3)	0.7	<0.0001*
	HF-LR (n = 46)	3.2 (2.2)	2.8 (2.4)	0.4	0.0287*
	LF-HR (n = 53)	5.7 (6.8)	5.1 (6.0)	0.6	0.0164*
	LF-MR (n = 290)	3.6 (4.5)	2.9 (4.2)	0.7	<0.0001*
	LF-LR (n = 174)	0.8 (1.8)	0.6 (1.3)	0.2	0.0003*
	Q-value	1.64	1.63		
Frequency of repetitive muscle activity (times/min)	HF-HR (n = 56)	17.8 (11.6)	18.6 (10.5)	−0.8	0.4157
	HF-MR (n = 114)	13.0 (7.8)	13.0 (7.4)	0.0	0.9380
	HF-LR (n = 46)	8.3 (4.1)	8.1 (4.8)	0.2	0.6177
	LF-HR (n = 53)	15.4 (11.3)	14.5 (11.2)	0.9	0.1864
	LF-MR (n = 290)	12.3 (8.1)	11.7 (7.3)	0.6	0.0913
	LF-LR (n = 174)	12.2 (10.3)	8.2 (6.3)	4.0	<0.0001*
	Q-value	2.74	1.98		
Duty cycle of forceful hand exertion (% time)	HF-HR (n = 56)	35.4 (23.5)	29.6 (20.6)	5.8	0.0666
	HF-MR (n = 114)	23.9 (19.4)	19.2 (18.6)	4.7	<0.0001*
	HF-LR (n = 46)	17.5 (11.5)	13.4 (9.0)	4.1	0.0020*
	LF-HR (n = 53)	12.6 (12.7)	10.4 (10.6)	2.2	0.0598
	LF-MR (n = 290)	13.6 (15.0)	9.3 (12.2)	4.3	<0.0001*
	LF-LR (n = 174)	4.8 (10.7)	3.0 (6.4)	1.8	0.0063*
	Q-value	1.46	1.40		
Duty cycle of repetitive muscle activity (% time)	HF-HR (n = 56)	54.6 (26.0)	51.8 (21.8)	2.8	0.1374
	HF-MR (n = 114)	58.8 (20.5)	51.8 (18.4)	7.0	<0.0001*
	HF-LR (n = 46)	56.4 (22.4)	52.7 (19.8)	3.7	0.1026
	LF-HR (n = 53)	51.9 (23.5)	48.9 (24.0)	3.0	0.1297
	LF-MR (n = 290)	64.8 (22.7)	60.4 (22.8)	4.4	<0.0001*
	LF-LR (n = 174)	49.7 (25.4)	41.6 (25.7)	8.1	<0.0001*
	Q-value	4.37	3.63		

*Significant difference at $p<0.05$.

†A 'forceful hand exertion' is defined as a lifting force of ≥8.9 N, a push/pull force of ≥44.5 N, a pinch grip force of ≥8.9 N or a power grip force of ≥44.5 N.

‡'Repetitive muscle activity' is defined as all 'required' hand and forearm muscle efforts during task performance.

§A combination of hand force (two levels: low (LF); high (HF)) and repetition (three levels: low (LR); medium (MR); high (HR)).

¶Difference = right hand force − left hand force.

Q-value = ratio of within-group standard deviation to between-group standard deviation (Fallentin *et al.* 2001).

between the different comparisons. One apparent pattern was that comparisons with more subjects seemed to show statistical significance ($p<0.05$) more often that those comparisons with fewer subjects (table 5).

4. Discussion

The individual exposure assessment approach, as used in the present study, appears to be capable of distinguishing differences in force levels and repetitiveness related to repetitive hand activities in jobs of different exposure levels. This applies to the different

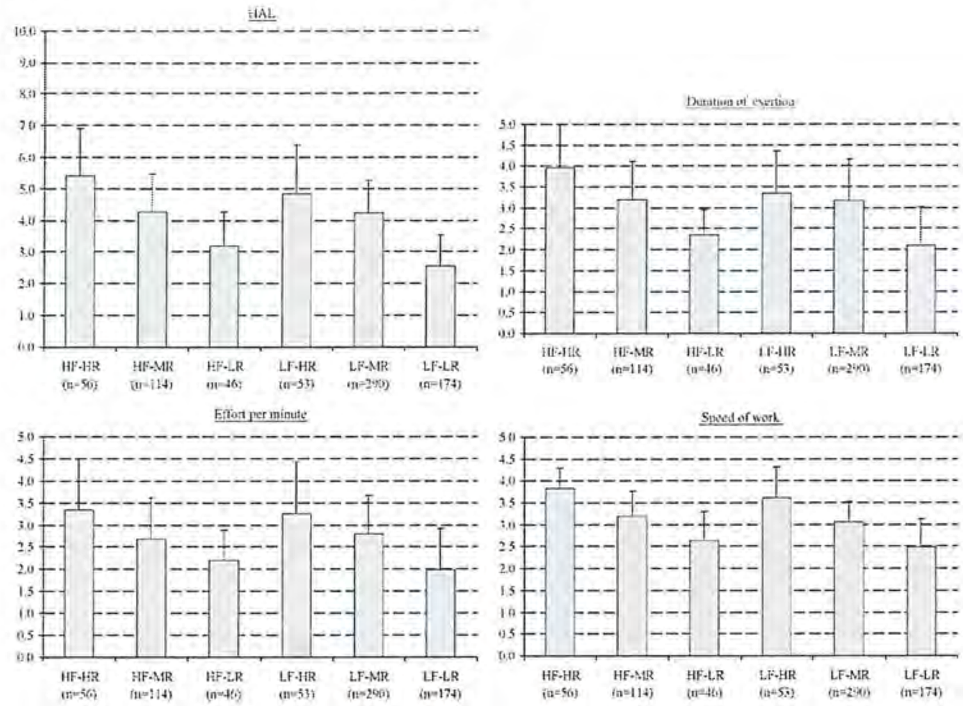

Figure 4. Average values and standard deviations of the ergonomist's estimated parameters in the different exposure categories (right hand only). The parameters are Hand activity level (HAL) (American Conference of Governmental Industrial Hygienists 2001); Duration of exertion; Efforts per minute; and Speed of work from the Strain Index (Moore and Garg 1995).

measurement methods used in the study to measure the force level and repetitiveness of hand activities.

A subjective determination of which forces are high enough to measure is a practical way to avoid measuring every force at work. Even with well-defined force levels, it is not possible to know the actual force level until it is measured. The ergonomists who made the judgements in this study appeared to have been conservative in their decisions to measure forces. Almost 9% of the measurements taken were lower than the defined levels for 'forceful exertion'. This was especially true for push/pull forces. One weak point of the present study is that it is not known whether any forces were missed that were greater than the operationally defined levels.

Force amplitude measurement results appear to be reasonable, based on their distribution across the different exposure categories and comparisons between left and right hand. High force exposure categories had higher average forces than low force exposure categories (figure 1 and table 3). The lack of significant differences between the right and left hand for lifting and push/pull forces (table 3) may be explained by the likelihood that lifting and pushing/pulling is usually a bilateral activity. The right hand power grip force is generally greater than the left hand (table 3). This is a reasonable result, as most people use their right hand to operate tools and machine controls when power grip hand postures are assumed. The lack of significant difference between left and right hand pinch grip force in high force jobs (table 3) can also be explained. Pinch grip

Table 5. Average values of the ergonomists' estimated parameters by hand and exposure category using the American Conference of Governmental Industrial Hygienists hand activity level (HAL) and the Strain Index methods.

	Exposure category†	Right hand Mean (SD)	Left hand Mean (SD)	Difference‡	*p*-value
HAL Score of 1–10	HF-HR (n = 56)	5.4 (1.5)	5.2 (1.6)	0.2	0.1768
	HF-MR (n = 114)	4.2 (1.2)	4.0 (1.2)	0.2	0.0096*
	HF-LR (n = 46)	3.2 (1.0)	3.1 (1.0)	0.1	0.2659
	LF-HR (n = 53)	4.8 (1.6)	4.6 (1.7)	0.2	0.0475*
	LF-MR (n = 290)	4.2 (1.0)	3.9 (1.1)	0.3	<0.0001*
	LF-LR (n = 174)	2.6 (1.0)	2.4 (1.0)	0.2	0.0002*
	Q-value	1.17	1.27		
Duration of Exertion Score of 1–5	HF-HR (n = 56)	4.0 (1.0)	3.9 (1.0)	0.1	0.4024
	HF-MR (n = 114)	3.2 (0.9)	3.0 (0.9)	0.2	0.0020*
	HF-LR (n = 46)	2.4 (0.6)	2.3 (0.6)	0.1	0.2094
	LF-HR (n = 53)	3.3 (1.0)	3.2 (0.9)	0.1	0.1982
	LF-MR (n = 290)	3.2 (1.0)	2.8 (1.0)	0.4	<0.0001*
	LF-LR (n = 174)	2.1 (0.9)	2.0 (0.9)	0.1	0.0004*
	Q-value	1.33	1.32		
Efforts per min Score of 1–5	HF-HR (n = 56)	3.3 (1.2)	3.3 (1.3)	0.0	0.2069
	HF-MR (n = 114)	2.7 (0.9)	2.5 (0.9)	0.2	0.0010*
	HF-LR (n = 46)	2.2 (0.7)	2.1 (0.7)	0.1	0.0310*
	LF-HR (n = 53)	3.2 (1.2)	3.1 (1.1)	0.1	0.1292
	LF-MR (n = 290)	2.8 (0.9)	2.5 (0.9)	0.3	<0.0001*
	LF-LR (n = 174)	2.0 (0.9)	1.8 (0.9)	0.2	<0.0001*
	Q-value	1.77	1.74		

(*continued*)

Table 5. (*Continued*)

	Exposure category†	Right hand Mean (SD)	Left hand Mean (SD)	Difference‡	p-value
Speed of Work Score of 1–5	HF-HR (n = 56)	3.8 (0.5)	3.7 (0.7)	0.1	0.0682
	HF-MR (n = 114)	3.2 (0.6)	3.2 (0.6)	0.0	0.3326
	HF-LR (n = 46)	2.6 (0.7)	2.6 (0.7)	0.0	0.3227
	LF-HR (n = 53)	3.6 (0.7)	3.6 (0.7)	0.0	0.1555
	LF-MR (n = 290)	3.1 (0.5)	3.0 (0.5)	0.1	0.0007*
	LF-LR (n = 174)	2.5 (0.5)	2.5 (0.6)	0.0	0.0864
	Q-value	1.13	1.28		

*Significant difference at $p < 0.05$.

†A combination of hand force (two levels: low (LF); high (HF)) and repetition (three levels: low (LR); medium (MR); high (HR)).

‡Difference = right hand force − left hand force.

Q-value = ratio of within-group standard deviation to between-group standard deviation (Fallentin *et al.* 2001).

postures were often used with both hands when lifting a heavy flat object. The significant difference between right and left hand pinch grip force in the LF-MR and LF-LR jobs (table 3) was likely a result of handling light objects at a relaxed pace and, therefore, one hand was usually sufficient for completing the task. When the work pace increased, the other hand may have been required to help. This was reflected in the insignificant difference between the left and right hand pinch grip force in the LF-HR jobs (table 3).

Frequency and duty cycle results for the forceful hand exertion analysis and repetitive muscle activity analysis are also reasonable. Jobs in the HF-HR exposure category are reflected by higher frequency and longer duration (higher duty cycle) values in the forceful hand exertion analysis when compared to jobs in the LF-LR category (figures 2 and 3). For jobs in the low force exposure categories, although time spent on forceful hand exertion may be short (reflected as lower duty cycles in the forceful hand exertion analysis in figure 3), the hand may still be actively in use. The relatively long duty cycles for repetitive muscle activity in low force exposure categories (figure 3), along with the lack of significant correlation between the frequency and duty cycle for repetitive muscle activity analysis, supports this hypothesis.

The right hand seemed to be more active in forceful exertions, as reflected by the higher frequency for the right hand in the forceful hand exertion analysis (table 4). The left hand may still have been involved in task performance, although without forceful hand exertion. This is illustrated by the similar frequencies shown for both the left and right hands in the repetitive muscle activity analysis (table 4). These differences may suggest different underlying physiological phenomena when the two different repetitiveness definitions were used.

The ergonomist's estimated parameters of frequency and duty cycle (HAL and the three Strain Index parameters) are reasonably distributed across the different exposure categories. This is not a surprise, as the job categorization was based on the ergonomist's subjective determination.

Comparison of the differences between the left and right hand showed a general trend of the right hand having higher ratings on HAL, duration of exertion, and efforts per minute (table 5). However, the significance levels are mixed across the different exposure categories with no easily explainable reason. In contrast to the detailed observation method for forceful hand exertion analysis, frequencies of the right hand were significantly higher ($p < 0.05$) than those of the left hand for all exposure categories (table 3). This difference between the two methods may be explained by the fact that the ergonomist's subjective estimations may be less specific when compared to detailed observations. Less specific methods generally require more subjects in order to detect existing differences (Woolson 1987). This is seen in the analysis where exposure categories such as HF-MR, LF-MR and LF-LR had more subjects and the right and left hand results showed significant differences (table 5). The left and right hand ratings for the speed of work were generally the same. This is reasonable as this is a parameter for the overall work pace rather than specific activities of the hand.

Comparisons of the different measurement methods for force and repetitiveness of hand activities were also conducted and these are reported in the companion paper (Bao *et al.* 2006).

Several researchers have pointed out that the commonly used approach of group exposure estimates is problematic in epidemiological studies of musculoskeletal disorders, as some exposure measurements are dependent on individual worker's characteristics (Burdorf 1993, Fallentin *et al.* 2001). However, few researchers have actually applied individual exposure assessment in epidemiological studies of musculoskeletal disorders.

Data from the present study have shown that exposure quantification of repetitive hand activity at the individual level is necessary, evidenced by the large exposure variation within the exposure categories. This seems to be particularly obvious for measures obtained from the detailed observational analysis of forceful hand exertions, evidenced by the wider confidence intervals and larger inter-subject CVs. Although the individual exposure assessment approach seems to be a preferable method to overcome the between-individual variability problem, a recent review article (Loomis and Kromhout, 2004) pointed out that estimates of exposure-disease association can be severely attenuated when the temporal component of exposure variability within people is large relative to that between individual subjects. Group-based assignments result in negligible attenuation. It is intended to study this issue further studied while performing exposure-disease modelling.

5. Conclusions

The individual exposure assessment approach was able to quantify force level and repetitiveness of hand activities. Repetitive hand activity is quantified differently depending on whether forceful hand exertion or repetitive muscle activity is used as the definition. These hand activity definitions may quantify different physical exposure phenomena.

Individual exposure assessment is important in epidemiological research of musculoskeletal disorders as there is an interaction between the individual subjects and the measured parameters. This interaction may vary between exposure parameters. Whether the effort spent in collecting such detailed exposure data at the individual level in large epidemiological studies is worthwhile for modelling the relationship between UEMSDs and exposure parameters remains to be seen.

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