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Reliable exposure assessment strategies for physical ergonomics stressors in construction and other non-routinized work

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The objective of this research was to provide guidelines for the reliable assessment of ergonomics exposures in non-routinized work. Using a discrete-interval observational sampling approach, two or three observers collected a total of 5852 observations on tasks performed by three construction trades (iron workers, carpenters and labourers) for periods of several weeks. For each observation, nine exposure variables associated with awkward body postures, tool use and load handling were recorded. The frequency of exposure to each variable was calculated for each worker during each of the tasks on each of the days. ANOVA was used to assess the importance of task in explaining between-worker and within-worker variability in exposures across days. A statistical re-sampling method (bootstrap) was used to evaluate the reliability of exposure estimates for groups of workers performing the same task for different sampling periods. Most exposures were found to vary significantly across construction tasks within trade, and between-worker exposure variability was generally smaller than within-worker exposure variability within task. Bootstrapping showed that the reliability of the group estimates exposure for the most variable exposures within task tended to improve as the assessment periods approached 5–6 d, with marginal improvements for longer assessment periods. Reliable group estimates of exposure for the least variable exposures within task were obtained with 1 or 2 d of observation. The results of this study demonstrate that an initial estimate of the important environmental or task sources of exposure variability can be used to develop an efficient sampling strategy that provides reliable estimates of ergonomics exposures during non-routinized work.

Keywords: Exposure assessment; Work sampling; Physical ergonomics stressors; Posture; Construction work; Bootstrap

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1. Introduction

Detailed information about the characteristics of jobs is needed in occupational musculoskeletal epidemiology and for the development of effective ergonomics controls when jobs are found to be problematic. While job title is a common surrogate for ergonomics exposure in epidemiological studies (Hagberg 1992, Burdorf 1993), using occupation as a surrogate for exposure when there is large variability in exposure within occupations can lead to exposure misclassification, which will decrease the magnitude of the association between exposure and health outcome when it exists (Burdorf 1993). Additionally, classification of ergonomics exposures by jobs does not provide very useful information required for the development of interventions. The importance of measuring ergonomics exposures with enough precision to aid in the development of effective controls has been expressed by others (Hagberg 1992, Winkel and Mathiassen 1994).

Ideally, analyses of jobs both in research and in practice are performed over a time period that is representative of the work activities. When the job is highly repetitive and is performed similarly by different people of the same occupation, the results of an exposure assessment performed on a small sample of workers can be generalized to the remainder of those performing the same or similar jobs. However, this is not true when the job is more variable or 'non-routinized', meaning that it cannot be easily characterized in terms of work cycles (repeated patterns of work activities or motions).

Much of the work performed in construction is non-routinized. This is due, to some extent, to the dynamic nature of construction work itself and the changing external environment, which impact the content and frequency distribution of job tasks across individuals and over time. It becomes immediately obvious that 1 d of observation is not enough, in contrast to the routinized production jobs that might be found in a stable environment, such as a factory. In addition to construction workers, agricultural workers, maintenance workers, healthcare workers and other service providers perform non-routinized work activities, although in some cases the environment itself might be more stable for these occupations.

In these non-routinized work situations, exposures may, in part, vary both across workers and over time for individual workers within an occupation because the distribution, duration and content of the work tasks may vary among individuals and over time. Such conditions require measurements across multiple workers over long work periods to capture a representative profile of the working conditions needed for reliable measures of mean exposures. Exposure assessments under these circumstances can often be very labour intensive and time-consuming. Winkel and Mathiassen (1994), among others, have indicated the need to develop efficient and reliable exposure assessment strategies for variable work.

Numerous discrete-interval observational sampling approaches have been developed to measure to the postural and physical demands of non-routinized work (e.g. Karhu *et al.* 1977, van der Beek *et al.* 1992, Buchholz *et al.* 1996). These methods offer the advantages of little interference to work and simultaneous evaluation of multiple exposures in real time. They can also be used in physically harsh environments, where the use of electronic direct measurements may not be feasible. While these methods have been used extensively to measure the physical requirements of jobs or job tasks performed by an occupation, one of the major disadvantages is that the data collection associated with the approaches can be extremely labour intensive. Therefore, the use of efficient and reliable exposure strategies is particularly important when these methods are used.

Exposure assessment strategies either involve directly measuring everyone in the study group or measuring a subset of the study group. Directly estimating exposure frequencies with discrete interval observations for all individuals in large study groups over long time periods is usually not feasible and, therefore, it is often necessary to apply exposure information collected for a subset of individuals to the larger study group when using these methods. Obtaining reliable measures of exposures for groups of workers requires knowledge about how exposures vary over time and among workers within a particular group, with an increasing number of samples required as exposure variability increases.

While much work has been dedicated to the evaluation of exposure variability for groups of workers performing the same job or job tasks in the study of chemical exposures (e.g. Rappaport 1991, Kromhout *et al*. 1993, Rappaport *et al*. 1993, Kromhout and Heederik 1995, Preller *et al*. 1995), what is known about how ergonomics exposures are distributed among workers and over time has been focused on the study of postural loading of the back or upper extremities and electromyographic activity of selected muscle groups in a few occupations (Burdorf 1992, 1995, Burdorf *et al*. 1994, van der Beek *et al*. 1995, Burdorf and van Riel 1996, Mathiassen *et al*. 2003, Moller *et al*. 2004). Other studies have recently evaluated the sources of exposure variability and offer strategies for exposure assessment for manual handling exposures (Paquet *et al*. 1999, van der Beek *et al*. 1999, Hoozemans *et al*. 2001). However, the variability of other ergonomics exposures, such as the postural loading on the upper and lower extremities, has not been evaluated as extensively. Therefore, the generalizability of these earlier findings to other ergonomics variables in non-routinized work activities is unknown.

Characterizing ergonomics exposures for tasks performed by groups of workers may be useful when there are great differences in exposures across tasks. Such an approach might be used to compare exposures among tasks, to evaluate the effectiveness of an intervention on exposures for a group of workers performing the same task or in epidemiological research to construct task-weighted exposure profiles for individual workers. The use of 'task' in the construction of exposure profiles for workers has been shown predictive of time-weighted mean chemical exposures among plant workers (e.g. Hansen and Whitehead 1988, Smith *et al*. 1997). Unfortunately, very little attention has been given to the formal evaluation of how task affects exposure to physical ergonomics stressors in non-routinized work, as well as the actual number of workers and amount of observation time needed for a reliable estimate of group exposures within tasks.

The objective of this research was to provide guidelines for the reliable assessment for a variety of ergonomics exposures in non-routinized work situations. Questions that were specifically addressed were: 1) To what degree will exposures vary across construction job tasks? 2) How do ergonomics exposures for tasks vary within and across workers? and 3) What is the minimum observation time needed to reliably characterize ergonomics exposures for groups of workers performing the same task?

2. Methods

2.1. *Study site, population and tasks performed*

The study site was a large highway and tunnel construction project located in Boston, MA, USA. This project was a multi-billion US dollar effort to build a tunnel under Boston Harbor and depress several miles of interstate highway underneath the city. It involved many contractors and subcontractors and thousands of construction workers over the course of the project. Ironworkers, labourers and carpenters were selected for the study because together these trades represented approximately one-half of the total workforce on the construction project.

A hierarchical framework or taxonomy that breaks down the construction process into stages, operations, job tasks and activities was developed to allow a systematic and detailed evaluation of ergonomics stressors for construction tasks (for descriptions, see Paquet *et al.* 1999, Moir *et al.* 2003). Stammers and Shepherd (1995) have noted that, although the concept of 'task' is central to most job analysis systems, there is no widely agreed-upon definition that is independent of the setting in which it is used. The job tasks of this taxonomy are defined similarly to Drury *et al.* (1987), in that tasks are defined as sequences of activities (or work elements) performed by an individual worker or a group of workers that accomplish a specific purpose or 'functional objective'. Tasks in this study were identified by interviewing workers and by direct observations of the work performed prior to the formal analysis of the ergonomics exposures. In the current study, each of the three trades was observed performing three or four tasks in three different construction operations.

In highway construction in the north-eastern USA, ironworkers are responsible for placing and connecting steel rods (rebar) that reinforce concrete structures (e.g. roadway bases, bridges, ramps and tunnels), labourers perform a variety of support tasks, which include pouring concrete, erecting scaffolding, housekeeping, stripping forms and manually excavating and fortifying shafts and tunnels, and carpenters construct the forms needed for pouring concrete structures. The evaluation was performed on ironworkers reinforcing concrete, labourers assisting with the construction of a utility shaft and carpenters building and erecting wooden and plastic forms.

Ironworkers were observed reinforcing concrete during the concrete masonry operation of the structures construction stage. Three major concrete-reinforcement job tasks included in the statistical analyses were: ground-level rebar construction; wall-rebar construction; and preparation work. Ground-level rebar construction involved the reinforcement of the sub-base surface of the highway. Wall rebar construction involved the reinforcement of vertical walls that divided the highway into two traffic directions and the outside walls. Preparation work included moving materials, guiding crane loads, erecting scaffolding along rebar walls and clearing debris. Two other tasks that were observed (caisson construction and supervision) were excluded from the analyses due to sparse data.

Labourers were observed while assisting in the construction of a jacking pit, a type of shaft used to install utilities such as drainage pipes and electrical ducts beneath the ground without the use of long trenches. This operation was part of the utilities relocation and installation construction stage. Four job tasks evaluated were: top work; manual excavation; pit-wall construction; and miscellaneous work. Top work was performed outside of the pit and involved cutting wood beams to specifications, directing a crane operator and monitoring the members of the crew who were in the pit. Pit-wall construction included burning holes into steel supports that lined the pit, retrieving wood beams from outside of the pit and attaching the wood beams to the supports. Manual excavation included using a jackhammer and shovelling debris into a crane's bucket. One job task (preparation work) was omitted from the analysis due to sparse data.

Carpenters were observed constructing forms during the cement–concrete–masonry operation of structures construction. Three tasks used in the analysis were building forms in a carpentry shop, building forms in the field and erecting forms. Building forms involved connecting sheets and boards together with nails, clamps and bolts. Table saws and workstations were used during the building of forms in the shop. Erecting forms involved working with a crane operator to guide the form into place and attaching the completed forms to rebar and concrete structures. Tasks observed but excluded from the analysis due to insufficient data included sawing/cutting, ventilation-form assembly, material handling, housekeeping, supervising and form stripping.

2.2. *Data collection*

PATH (Buchholz *et al.* 1996) was used to characterize ergonomics exposures for the tasks of each operation. The method allows good inter-observer reproducibility for the assessment of a variety of ergonomics exposures (Buchholz *et al.* 1996) and accurate measurement of broad body posture categories (Paquet *et al.* 2001) for construction tasks. Observations were made on the construction site at fixed, short intervals (45 – 60 s). At each observation, the observers recorded the task, body postures, activities, loads handled and tool used (if any) for a single worker, in a checklist-type format onto data coding sheets. Prior to formal data collection, PATH coders spent 2 – 3 d observing each operation, piloting the PATH data collection and checking inter-observer reliability of coding. Repeated observations were made to allow the frequency of the ergonomics exposures, measured as a percentage of the observations, to be estimated for tasks, workers and days.

In order to obtain estimates of exposures thought to be representative of the tasks within the operation, the sampling strategy required observing tasks performed by multiple workers across multiple days, over periods of several days or weeks. Two or three observers collected PATH data on workers in each trade. At the beginning of a workday, each observer selected a crew of four to ten workers to follow for sampling periods of 3 – 4 h. The ironworkers and carpenters were sampled in a random sequence within crews throughout each sampling period. For the labourers, each observer randomly selected a single worker to observe for the day. Each operation was observed for a total of 10 – 15 d over a period of 4 – 5 weeks. Crews often, but not always, included the same workers on subsequent days.

2.3. *Ergonomics exposure variables*

For each of the tasks, nine ergonomics exposure variables were extracted from the raw observational data and evaluated as present or absent at each observation:

- trunk flexion $\geq 20°$;
- lateral bending or torsion $\geq 20°$;
- any non-neutral trunk posture (flexion, lateral bending or torsion $\geq 20°$);
- arm(s) at or above shoulder height;
- kneeling, squatting or leg bending ($> 35°$);
- manual materials handling (MMH) (lift, lower, carry, move, push or pull) ≥ 44 N;
- moderate or heavy load handling (included MMH and non-MMH activities with load handling);
- hand-tool use;
- power-tool use.

The frequency of exposure was calculated as the ratio of the number of observations with the exposure to the total number of observations during a day. This was calculated by task, on each day, for individual workers who performed that task (individual daily exposure) and for the entire group of workers who performed the task (group daily exposure).

2.4. *Data analysis*

2.4.1. Data management. The data coding sheets were scanned into a personal computer using optical mark recognition software (Remark Office OMR, Principia Products, West Chester, PA, USA). Data were visually reviewed for scanning errors and corrected as necessary by manual data entry. The data were analysed with the statistical analysis system for the personal computer (Statistical Analysis System Institute 1992). Only daily task-specific exposure frequency estimates taken on multiple days for each worker were used in the analysis of variance models; therefore, the workers included in these analyses were subsets of the study group observed on site.

2.4.2. Exposure variability due to task within operation. A mixed-effects ANOVA model was used to determine the degree of exposure variability across tasks. The tasks performed by the trade within each operation were treated as a fixed-effect covariate and the worker as a random-effect covariate in this model. The levels of the fixed effect represented the population of levels under study (i.e. the tasks of an operation) and the levels of the covariance parameter (random effect) were thought to be drawn randomly from an infinite population of levels (i.e. a sample of workers drawn from a population of workers). As with the mixed-effects model, the task-specific exposure data for each individual worker were assumed to be normally distributed with zero mean, unknown variance and were hypothesized to be correlated. The F-statistic was used to test whether differences in mean exposure existed for the tasks within each operation after controlling for any worker effect.

2.4.3. Between-worker and within-worker components of variance within task. For each task, the within- and between-worker components of variance were evaluated again for only those workers observed performing the same task on multiple days. A random effects ANOVA with worker as a random effect was used. The percentage of total variance attributed among workers and within workers was then calculated from the variance estimates produced by the model. The between-worker variance represented differences in mean exposure frequency among individual workers. The within-worker variance component was interpreted to be largely attributed to day-to-day differences in exposure associated with the changing environment, differences in work methods used and differences in amount of time devoted to activities within the tasks, although measurement error was also reflected in this component of variance.

2.4.4. Bootstrapping to evaluate the number of days needed for reliable exposure assessment. Bootstrapping was used to simulate the obtained daily-group estimates of exposure for assessment periods of 1 d up to the total number of days in each dataset using Stata software (Stata Corporation 1997). Bootstrapping is a statistical approach that allows inferences to be made without strong assumptions about a sample's population distribution. Instead, the major assumption of this approach is that the distribution within a sample approximates that of the population of interest (i.e. that the sample is unbiased). The distributional properties of the population parameter are estimated by sampling the original study population repeatedly with replacement.

Bootstrapping first requires the construction of an empirical probability distribution from a sample by placing a probability of 1 n (where n is the number of measurements in the sample) at each of the original sample's points. A sample (or set) of size n (where n is a number $\leq$n) is then drawn with replacement from the empirical probability distribution. The statistic of interest is calculated from the sets of 're-samples'. The re-sampling of the empirical probability distribution and statistical calculation is then repeated many times. A probability distribution of the statistic is then constructed from the re-samples by placing a probability of 1 x (where x is the number of re-samples) at each point. This probability distribution is the bootstrapped estimate of the population's distribution for the statistic. To construct confidence intervals around the statistic of interest, at least 1000 re-samples are recommended (Mooney and Duval 1993). A more detailed description of the statistical approach is offered by Hoozemans *et al.* (2001).

For each simulated observation period in this study, mean daily exposure for each exposure-task combination was calculated with aggregate data from all workers on each observation day to provide a group mean daily exposure across multiple days (i.e. mean daily exposures were calculated with observational data for all workers performing the same task on a day). Daily group exposure estimates based on fewer than 40 observations for a task were excluded from the analyses.

Mean daily estimates of group exposure within task were bootstrapped to evaluate the reliability of different observational assessment periods that estimated ergonomics exposures for tasks. For a given assessment period of 1 up to 10 d, 1000 samples of daily group exposure were drawn with replacement from the empirical distribution of the original sample, and the mean daily group exposure estimate was calculated for each of the 1000 samples. For example, assessment periods of 3 d would require three daily estimates of exposure to be drawn with replacement from the original exposure distribution and averaged, and this procedure would be repeated 1000 times. The mean and upper and lower boundaries of the 95% CI were plotted against the different observational periods for different tasks and exposures. A narrowing of the confidence interval was considered to be an improvement of exposure assessment reliability as this indicates an improvement on the consistency of the exposure estimate for repeated trials.

3. Results

3.1. *Exposure variability among tasks*

A total of 5852 observations were made on ten construction tasks (table 1). For the ironworkers, a total of 1790 observations were made on three tasks (ground-level rebar construction, wall-rebar construction and preparation work). For the labourers, 3219 observations were made on four tasks (top work, manual excavation, pit-wall construction and miscellaneous work). A total of 843 observations were made on three carpentry tasks (building forms in a carpentry shop, building forms in the field and erecting forms). The task of 'supervision', which was performed by one or two workers exclusively during each operation and was associated with much lower physical requirements, was excluded from the analysis.

There were often large differences in exposure frequency among the tasks performed by each trade. For the ironworkers, there were statistically significant differences in exposure frequency among tasks ($p < 0.05$) for six of the nine ergonomics variables tested (table 2). Significant differences in exposure frequency among the labourers' tasks ($p < 0.05$) were

Table 1. Summary of data collected for the three highway construction operations.

Operations and job tasks	Observations	Workers	Days
Concrete reinforcement			
Ground-level rebar construction	623	17	11
Vertical wall rebar construction	516	15	10
Preparation work	651	16	13
Operation total	1790		
Utility pit construction			
Top work	709	7	9
Pit wall construction	563	9	10
Manual excavation	1416	10	13
Miscellaneous	531	10	10
Operation total	3219		
Form construction			
Building forms in a shop	322	4	6
Building forms on site	187	8	8
Form erection	334	7	7
Operation total	843		
Total	**5852**		

Table 2. Summary of the exposure frequencies across task and between worker variance within task (ironworkers)†.

Exposure	Ground-level rebar construction	Vertical wall rebar construction	Preparation work
Non-neutral trunk**			
No. of workers	7	7	5
Total no. of person days of exp.	20	20	15
Max repeats per worker	4	4	4
Mean exposure (% time)	**52.0**	**38.9**	**32.3**
SD	**16.0**	**15.3**	**11.3**
% Variance due to worker	**0**	**6.9**	**0**
Flexed trunk**			
No. of workers	6	7	5
Total no. of person days of exp.	20	20	15
Max repeats per worker	4	4	4
Mean exposure (% time)	**41.0**	**27.8**	**24.9**
SD	**16.6**	**13.5**	**11.1**
% Variance due to worker	**0**	**5.9**	**3.9**
Laterally bent or twisted trunk			
No. of workers	6	7	5
Total no. of person days of exp.	20	20	15
Max repeats per worker	4	4	4
Mean exposure (% time)	**28.2**	**22.4**	**20.3**
SD	**14.6**	**14.7**	**10.7**
% Variance due to worker	**0**	**0**	**18.4**
Load handling			
No. of workers	6	6	5
Total no. of person days of exp.	20	17	15

(*continued*)

Table 2. (*continued*)

Exposure	Ground-level rebar construction	Vertical wall rebar construction	Preparation work
Max repeats per worker	4	4	4
Mean exposure (% time)	**18.9**	**14.2**	**19.2**
SD	**11.3**	**14.6**	**7.7**
% Variance due to worker	**0.6**	**7.0**	**8.2**
Arm(s) at or above shoulder height			
No. of workers	6	7	5
Total no. of person days of exp.	20	20	15
Max repeats per worker	4	4	4
Mean exposure (% time)	**6.2**	**8.9**	**7.7**
SD	**5.9**	**10.6**	**8.6**
% Variance due to worker	**0**	**59.5**	**0**
Kneeling, squatting or leg bending**			
No. of workers	6	7	5
Total no. of person days of exp.	20	20	15
Max repeats per worker	4	4	4
Mean exposure (% time)	**34.8**	**16.6**	**12.6**
SD	**16.6**	**13.5**	**7.8**
% Variance due to worker	**31.2**	**9.6**	**0**
Hand-tool use*			
No. of workers	6	7	4
Total no. of person days of exp.	20	18	11
Max repeats per worker	4	4	4
Mean exposure (% time)	**15.6**	**11.2**	**3.2**
SD	**15.5**	**8.6**	**4.6**
% Variance due to worker	**0**	**0**	**0**
Power-tool use**			
No. of workers	5	7	4
Total no. of person days of exp.	16	18	11
Max repeats per worker	4	4	4
Mean exposure (% time)	**0.5**	**3.0**	**9.7**
SD	**1.6**	**8.6**	**10.1**
% Variance due to worker	**20.1**	**0**	**47.4**
Materials manual handling**			
No. of workers	6	7	5
Total no. of person days of exp.	20	20	15
Max repeats per worker	4	4	4
Mean exposure (% time)	**28.7**	**12.1**	**18.9**
SD	**16.6**	**13.2**	**10.6**
% Variance due to worker	**0**	**10.0**	**29.0**

Significant differences in exposure among tasks, $*p < 0.05$ (F test).
Significant differences in exposure among tasks, $**p < 0.01$ (F test).
†Included are the number of workers included in the analysis, total number of person days of exposure data, the maximum number of repeated measurements for a worker, standard deviation of the daily exposure measurements for individuals and percentage of the total sample variance attributed to worker.

found for six of the nine variables (table 3), five of which were also found statistically significant in the analysis of the ironworkers' tasks. There were significant differences in exposure frequency among carpentry tasks ($p < 0.05$) for four of the nine exposure variables (table 4).

Table 3. Summary of result of the mixed-effects models to evaluate the importance of construction task on exposure frequency in utility pit construction tasks (labourers).

Exposure	Top work	Wall construction	Manual excavation	Miscellaneous
Non-neutral trunk**				
No. of workers	2	4	4	4
Total no. person-days of exp.	4	9	11	9
Max repeats per worker	2	3	3	3
Mean exposure (% time)	**38.3**	**54.5**	**44.4**	**17.5**
SD	**19.1**	**17.7**	**24.7**	**15.2**
% Variance due to worker	**0**	**0**	**59.0**	**0**
Flexed trunk**				
No. of workers	2	4	4	4
Total no. of person days of exp.	4	9	11	9
Max repeats per worker	2	3	3	3
Mean exposure (% time)	**30.8**	**47.5**	**39.1**	**13.5**
SD	**20.5**	**14.7**	**22.2**	**13.0**
% Variance due to worker	**0**	**0**	**62.0**	**0**
Laterally bent or twisted trunk				
No. of workers	2	4	4	4
Total no. of person days of exp.	4	9	11	7
Max repeats per worker	2	3	3	3
Mean exposure (% time)	**6.6**	**7.6**	**16.2**	**2.5**
SD	**1.1**	**4.2**	**23.5**	**4.3**
% Variance due to worker	**0**	**0**	**13.2**	**0**
Load handling**				
No. of workers	2	4	4	4
Total no. of person days of exp.	4	9	11	9
Max repeats per worker	2	3	3	3
Mean exposure (% time)	**22.5**	**47.9**	**46.5**	**6.7**
SD	**14.3**	**20.0**	**27.3**	**10.7**
% Variance due to worker	**0**	**0**	**64.1**	**10.7**
Arm(s) at or above shoulder height				
No. of workers	2	3	4	4
Total no. of person days of exp.	4	7	10	9
Max repeats per worker	2	3	3	3
Mean exposure (% time)	**9.4**	**3.5**	**6.5**	**6.6**
SD	**7.7**	**2.7**	**4.1**	**5.3**
% Variance due to worker	**0**	**0**	**0**	**21.5**
Kneeling, squatting or leg bending*				
No. of workers	2	4	4	4
Total no. of person days of exp.	4	9	11	9
Max repeats per worker	2	3	3	3
Mean exposure (% time)	**27.8**	**46.5**	**40.2**	**20.7**
SD	**15.1**	**15.9**	**19.7**	**14.9**
% Variance due to worker	**0**	**0**	**25.1**	**0**
Hand-tool use**				
No. of workers	2	4	4	3
Total no. of person days of exp.	4	9	11	7
Max repeats per worker	2	3	3	3

(*continued*)

Table 3. (*continued*)

Exposure	Top work	Wall construction	Manual excavation	Miscellaneous
Mean exposure (% time)	**10.1**	**23.2**	**36.7**	**10**
SD	**7.4**	**17.0**	**24.9**	**2.5**
% Variance due to worker	**0**	**0**	**46.2**	**13.7**
Power-tool use				
No. of workers	2	3	3	3
Total no. of person days of exp.	4	7	8	7
Max repeats per worker	2	3	3	3
Mean exposure (% time)	**7.6**	**15.9**	**6.2**	**0**
SD	**5.2**	**21.2**	**7.5**	**0**
% Variance due to worker	**44.6**	**0**	**0**	**n/a**
Materials manual handling*				
No. of workers	2	4	3	4
Total no. of person days of exp.	4	9	8	9
Max repeats per worker	2	3	3	3
Mean exposure (% time)	**7.1**	**6.6**	**1.1**	**0.8**
SD	**4.8**	**8.2**	**2.0**	**1.4**
% Variance due to worker	**70.2**	**19.1**	**0**	**81.7**

Significant differences in exposure among tasks, *$p < 0.05$ (F test).
Significant differences in exposure among tasks, **$p < 0.01$ (F test).

Table 4. Summary of result of the mixed-effects models to evaluate the importance of construction task on exposure frequency in form construction tasks (carpenters).

Exposure	Form building in a shop	Form building on site	Form erection
Non-neutral trunk**			
No. of workers	3	3	4
Total no. of person days of exp.	9	7	11
Max repeats per worker	4	3	4
Mean exposure (% time)	**33.8**	**46.4**	**61.0**
SD	**14.6**	**9.7**	**16.9**
% Variance due to worker	**29.0**	**0**	**0**
Flexed trunk			
No. of workers	3	3	4
Total no. of person days of exp.	9	7	11
Max repeats per worker	4	3	4
Mean exposure (% time)	**25.7**	**34.3**	**37.0**
SD	**13.1**	**12.5**	**20.0**
% Variance due to worker	**48.5**	**0**	**48.5**
Laterally bent or twisted trunk**			
No. of workers	3	3	4
Total no. of person days of exp.	9	7	11
Max repeats per worker	4	3	4
Mean exposure (% time)	**18.7**	**18.9**	**44.6**
SD	**11.1**	**6.4**	**13.5**
% Variance due to worker	**0**	**0**	**0**

(*continued*)

Table 4. (*continued*)

Exposure	Form building in a shop	Form building on site	Form erection
Load handling			
No. of workers	3	2	4
Total no. of person days of exp.	6	4	10
Max repeats per worker	4	2	3
Mean exposure (% time)	**15.8**	**5.9**	**4.6**
SD	**13.5**	**4.4**	**4.9**
% Variance due to worker	**0**	**74.6**	**50.7**
Arm(s) at or above shoulder height*			
No. of workers	3	3	4
Total no. of person days of exp.	8	7	11
Max repeats per worker	2	3	4
Mean exposure (% time)	**4.2**	**7.8**	**11.4**
SD	**3.9**	**5.6**	**6.6**
% Variance due to worker	**0**	**54.7**	**0**
Kneeling, squatting or leg bending			
No. of workers	3	3	4
Total no. of person days of exp.	9	6	11
Max repeats per worker	4	2	4
Mean exposure (% time)	**15.5**	**25.5**	**24.5**
SD	**12.8**	**17.7**	**14.0**
% Variance due to worker	**13.0**	**0**	**34.2**
Hand-tool use			
No. of workers	3	2	4
Total no. of person days of exp.	9	5	11
Max repeats per worker	4	3	4
Mean exposure (% time)	**12.2**	**12.2**	**9.6**
SD	**8.1**	**8.4**	**7.3**
% Variance due to worker	**0**	**0**	**86.0**
Power-tool use**			
No. of workers	3	2	4
Total no. of person days of exp.	9	5	9
Max repeats per worker	4	3	3
Mean exposure (% time)	**11.6**	**4.4**	**0**
SD	**7.0**	**4.7**	**0**
% Variance due to worker	**0**	**69.4**	**n/a**
Materials manual handling			
No. of workers	3	3	4
Total no. of person days of exp.	9	7	11
Max repeats per worker	4	3	4
Mean exposure (% time)	**19.7**	**12.8**	**16.6**
SD	**6.4**	**7.4**	**7.6**
% Variance due to worker	**0**	**0**	**16.3**

Significant differences in exposure among tasks, *$p < 0.05$ (F test).
Significant differences in exposure among tasks, **$p < 0.01$ (F test).

The between-worker component of exposure variability was relatively small compared to the intra-worker exposure variability for the tasks performed by the ironworkers and the labourers (tables 2 and 3), perhaps due to the relatively small numbers of repeated observation days for each worker. Between-worker variance was less than 10% of the total exposure variance for almost all of the exposures within each task and exceeded the within-worker variability only in a few cases. For the carpenters, very little exposure variance was also explained by differences across workers in most form-construction tasks. However, exposures to load handling and arms at or above shoulder height during form building on site, and exposure to load handling and hand-tool use during form erection, had between-worker variance components that exceeded the corresponding within-worker exposure variance components (table 4).

3.2. *Evaluation of number of observation days for reliable exposure assessment*

There were six construction tasks (three for ironworkers, two for labourers and one for carpenters) that had at least 40 observations on multiple workers per day for multiple days and were deemed eligible for analysis. For the nine exposures evaluated in each of these tasks, the reliability of the exposure estimates generally increased with increasing observation periods. Similar trends were found for high, medium and low exposure variability conditions regardless of the mean frequency of exposure, although the low frequency exposures tended to be less variable and therefore would generally require fewer days of observation. As expected, the improvement in the exposure estimate over time was most pronounced for the high-variability conditions and least dramatic in the low-variability conditions.

The bootstrap results for exposure variables representing three levels of between-day group exposure variability are illustrated here (figure 1a,b,c). These represent lower, middle and upper thirds of exposure between-day variance estimates obtained for variables in which at least 6 d of observation could be simulated. The variables were kneeling, squatting or leg bending during the labourers' task manual excavation (high variability), trunk flexion during the ironworker's task of ground-level rebar construction (medium variability), and MMH during the labourer's task of pit-wall construction (low variability).

For the highest between-day exposure variability case, the bootstrap results revealed extremely wide confidence intervals for observation periods of 1–3 d with dramatic improvements in reliability as assessment periods increased from 1 d ($\pm$30%, 95% CI) to 5 d ($\pm$15%, 95% CI) (figure 1a). The confidence interval decreased very little for observation periods exceeding 6 d. For the medium exposure variability case, a precision of $\pm$15% (95% CI) in the exposure frequency estimate was obtained for assessment periods of 1 and 2 d of observation, with a narrowing to $\pm$8% for assessment periods of 6 d (figure 1b). The level of precision for the low exposure variability case was $\pm$4% (95% CI) for observation periods of 1 d and $\pm$2% for observation periods of 7 d (figure 1c).

4. Discussion

4.1. *Characterizing exposures for tasks*

Statistically significant differences in exposure frequency among tasks were found in over one-half of the tests for the three construction trades evaluated in this study. This was often in spite of both low precision in the measurement of workers' daily exposure frequencies (few observations per person per task per day) and a small number of daily exposure measures for each task within an operation. Additionally, the task definitions did not necessarily and were not intended to maximize the contrast of exposure across tasks for all of the different ergonomics exposures studied here. Instead, each trade's tasks were defined so that contractors, workers and those who made the observations could easily

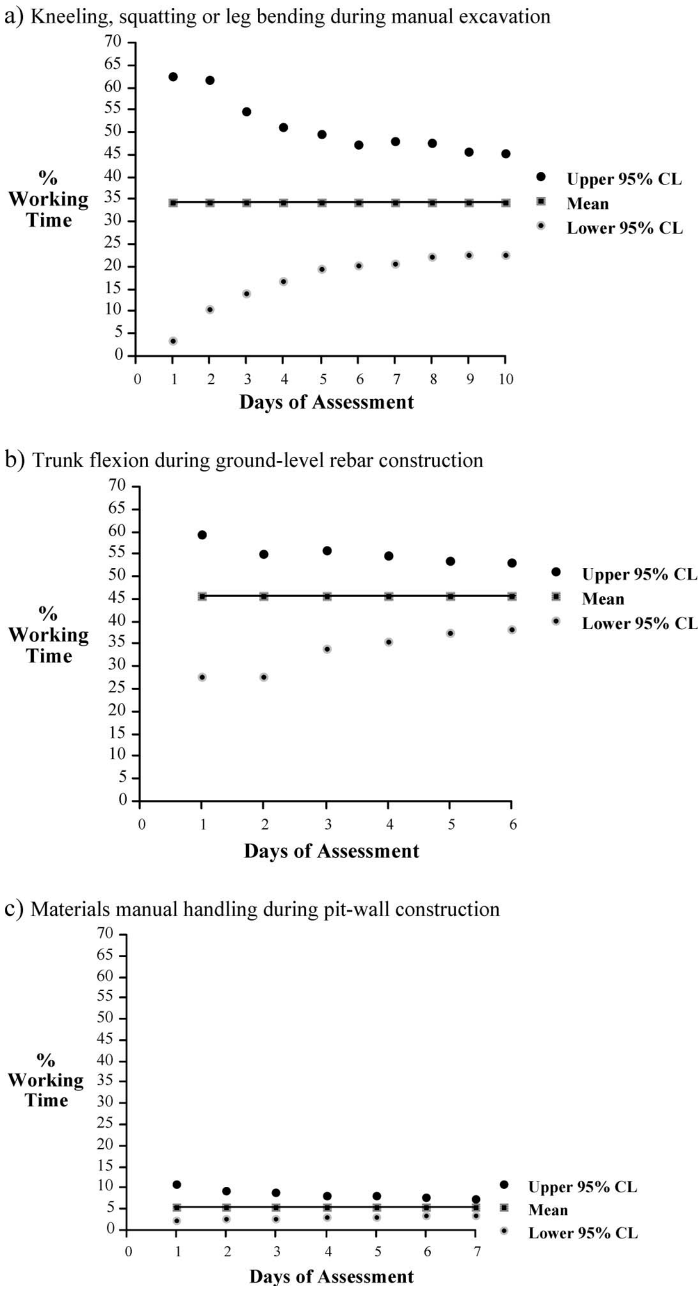

Figure 1. Mean exposure frequency estimates (% of observations) from bootstrap analysis for high, medium and low variability exposures cases. a) High: kneeling squatting or leg bending during manual excavation (mean 35.2, SD 18.9); b) Medium: trunk flexion during ground rebar construction (mean 45.8, SD 10.7); c) Low: manual material handling during pit-wall construction (mean 5.4, SD 3.0).

understand the task definitions. The large difference in exposure frequencies among many tasks observed here provides evidence supporting this task-based strategy as a viable way to enhance the characterization of exposure for groups of skilled-trades workers. Approaches such as these have also been used effectively to quantify the role of important factors that contribute to metal-working fluids exposures in the automobile industry (Woskie *et al.* 1994). The quantification of exposures by tasks also provides the level of detail needed for the identification and evaluation of ergonomics controls designed to reduce exposures associated with specific tasks (e.g. improved hand tools or MMH aides).

The statistical analysis used in the study can be applied to evaluate the exposure assessment strategies for different work settings and for job characteristics other than task. Alternative methods of partitioning the exposures of a job might include, for example, categorizing exposures that occur at specific workstations or exposures that are present inside vs. outside. The choice on how to divide jobs in ways that are meaningful in terms of varying exposure levels will depend on the researchers' or practitioner's prior beliefs about the important sources of exposure variability and the purpose of the assessment (e.g. epidemiology or ergonomics practice).

The actual exposure frequencies obtained for the construction tasks evaluated in this study are based on the assumption that the time period and workers measured allow an unbiased estimate of the exposure for each task. When the assessments are not made on a representative sample of a defined exposure group, or when members of these groups do not, in fact, have similar exposures, a biased exposure estimate for the group is likely. It should be noted that measurements were made on fairly large groups of workers over observational periods of several weeks in order to reduce the chance of biased exposure estimates. However, measurements were not made on all possible environmental conditions that construction workers might experience while performing the tasks and cold weather and night work was probably under-represented in the assessment. The group exposures obtained for these tasks should therefore not be generalized to these conditions if such factors are thought to affect exposure levels.

4.2. *Between worker exposure variance within exposure groups (tasks)*

The effects of the between-worker and between-day variability in exposure from earlier studies of non-routinized work were used in the development of the present data collection protocol, which required measurements to be made on multiple workers over the course of most of the workday in order to estimate daily exposure estimates for groups of workers performing the same task. Burdorf (1992) showed that exposures to the low back could vary from three to as much as 36 times among workers of the same occupation, indicating a need to assess multiple workers. Van der Beek *et al.* (1995) found that the variance of exposure to non-neutral trunk postures within workers over the course of 1 d explained approximately 80% of the total variance of exposure within occupation for five different occupations including truck drivers, garbage collectors, shipment loaders, warehouse workers, nurses and fork truck drivers, suggesting that it is important to evaluate the worker for the entire day. In a study of the frequency and duration of pushing and pulling among train stewards and nurses, Hoozemans *et al.* (2001) found that approximately one-half day of exposure assessment and no more than ten workers were needed to provide a reliable estimate of group exposure over the course of a day. Observations in the present study were made on groups of workers over multiple days throughout most of each work shift in order to account for the exposure variability within and across workers.

In this study, the between-worker exposure variance within a task was often quite small when compared to the within-worker variance component. This suggests that task-specific ergonomics exposures may be similar across workers performing the same construction task over time and supported the need to collect data on multiple days. However, the lack of precision in the daily exposure frequency for individuals within tasks and the relatively small number of workers per task may have, in some cases, inflated the within-worker exposure variance, which would have reduced the estimate of exposure explained by worker.

The statistical models used to evaluate exposure variability in this study were selected, to a certain extent, based on the distribution of exposures and the unbalanced nature of the datasets. The measure of exposure variability thought to be appropriate to describe exposures was the standard deviation of the daily exposure measurements. In earlier statistical tests of the exposure distributions, the data were in most cases normally distributed, which has been generally found to be true in earlier studies that have evaluated the variability of low back postures over time (e.g. Burdorf *et al.* 1994, van der Beek *et al.* 1995). In both the mixed-effects and random-effect models, the restricted maximum likelihood (REML) method was used to estimate the components of variance. This method was chosen over others because workers were crossed with tasks in the mixed-effects model and there were unequal numbers of observation days for individual workers in both models. Whilst there is no one best computational method for estimating variance components in all situations, the REML method appears to be favoured over other methods for estimating the components of variance in crossed-unbalanced designs (Lindman 1974). Because random effects are variables for which the selected levels are thought to be drawn from an infinite or very large population of levels, one of the qualities of the analysis of random effects is that the results can be generalized beyond the random-effects levels used in the analysis (Lindman 1974). Different statistical models for evaluating exposure variance could be used if other exposure assessment designs are used (e.g. balanced across workers and tasks).

The contributions of the between-worker and within-worker exposure variability varied across the exposure variables included in this study. In a previous study of upper torso and upper extremity postures and electromyographic activity during simulated automotive assembly tasks, Mathiassen *et al.* (2003) also found that the variability within and across subjects was highly dependent on the exposure variable. As the variability in exposure within and across individuals in a study group increases, it is necessary to increase the number of measurements for a reliable estimate of exposure. Therefore, studies that attempt to characterize multiple exposures simultaneously should be designed to reliably estimate the most variable exposures in order to ensure reliable estimates of all of the variables considered.

4.3. *Reliability of assessment strategies*

The sources of exposure variability across days, within the course of a day and across workers were all originally thought to be important prior to the current study due to the non-routinized nature of construction work. Since in the present case the within-worker variability, due, at least in part to day-to-day exposure variability, later appeared to be more important than the between-worker exposure variability, group exposure information for multiple days was used to determine the length of the observation period for reliable exposure estimates. Specifically, the bootstrap approach was used to determine the optimum number of days that groups of workers needed to be sampled throughout the entire day in order to obtain reliable estimates of mean group exposure for the nine physical ergonomics exposures. This approach differed slightly from previous studies that have applied the statistical procedure to exposure data of individual workers in order evaluate assessment strategies for ergonomics exposures (e.g. Burdorf and van Riel 1996, Hoozemans *et al.* 2001).

The improvement in reliability associated with increasing the number of measurement days reported here has been influenced partially by limitations in the sampling, which led to unequal numbers of workers and observations per worker in the calculation of the mean group daily exposure estimates. If, for example, the group daily exposure estimate was based upon different small subsets of workers on different days, exposure variability attributed to day would be completely confounded by worker. However, this was not the case in this study. On every day of observation, observations were attempted on all individuals enrolled in the study and most of the employees were observed. The unequal number of observations on workers within day and task can be attributed to the different proportions of time that different workers spent completing different tasks, missed observations due to obstructed views or absenteeism of the employee, and the random order in which observations were made across workers, which would not guarantee equal numbers of observations for workers within tasks. A dataset balanced in terms of the number of days and the number of observations per day included for workers within tasks would allow a more accurate understanding of the true impact of increasing the observation days on the reliability of the exposure assessment for different variables. However, the effects of worker on exposure variability for the tasks studied here were relatively low. Additionally, in cases where many discrete-interval observations are made over long time periods on groups of workers, it is unlikely that such a balanced dataset can be obtained. Instead, the bootstrapping approach used here was intended to realistically simulate exposure assessment efforts for which researchers or practitioners might not be able to estimate group mean daily exposures within tasks using observational methods having samples completely balanced across workers, tasks and days. Such an approach would seem appropriate when inter-worker contribution to exposure variability is low when compared to the other sources of exposure variability.

The need to perform assessments on multiple days for reliable exposure estimates for exposures with high day-to-day variability is a concept addressed in many texts on exposure assessment (e.g. Boleij *et al.* 1995), but practical methods for determining the necessary assessment periods for reliable exposure estimates that do not rely heavily on statistical assumptions about the population distribution are rarely discussed. In this study, a systematic method was used to evaluate the reliability of different assessment strategies evaluated by simulating exposure assessment periods repeatedly (1000 times) and evaluating the reproducibility of the results through the use of a 95% CI. This illustrated the importance of evaluating ergonomics exposures for groups of workers on multiple days to improve the reliability of the exposure, particularly when exposure frequencies are variable. As expected, exposures that had less variability across within-task variable could be effectively estimated with shorter observation times.

One of the most important limitations of the bootstrap approach used in this study was the number of observation days from which the samples were drawn. Small samples are particularly problematic for the calculation of bootstrapped confidence intervals, as the upper and lower tails of the population distribution may not be represented (Mooney and Duval 1993). In construction work, some trades and individuals experience a wide variety of job demands and it is conceivable that observation periods of greater than 10 d could be needed to capture a better representation of the population distribution of daily group exposures for the tasks. The bootstrap approach used in this study, when applied to larger datasets could be used to further improve exposure assessment strategies for epidemiological research and for the identification and evaluation of controls in non-routinized work.

This study focused on exposure assessment methods designed to obtain reliable estimates of long-term group mean exposure to different physical ergonomic stressors. There are, of course, other exposure metrics that may be important for epidemiological research or intervention evaluation. For example, van der Beek *et al.* (1999) summarized a method of characterizing cumulative peak external exposures to pushing and pulling tasks. These cumulative peak exposures can be used to characterize exposures to individuals or groups over the course of a selected time period. If repeated measurements are made across workers repeatedly over time, the worker-dependent and time-dependent sources of exposure variability can be better understood and strategies for the reliable estimate of exposures can be developed. Van der Beek *et al.* (1999) evaluated sources of exposure variability for truck drivers and refuse collectors and recommended five repeated measurements of each representative work situation to obtain a reasonable estimate of an individual's mean cumulative exposure to pushing and pulling. Further analysis would be needed to better understand the exposure assessment strategies to employ in order to obtain reliable group estimates of exposure for each occupation.

5. Recommendations

The following recommendations, which are based on the methods used and results of this study, are intended to help researchers and practitioners develop exposure assessment strategies for the reliable estimate of mean group exposure to physical ergonomics stressors in non-routinized work activities:

1. For jobs in which the exposures are thought to vary, identify the potential environment or task sources of exposure variability before beginning data collection. Initially, these may be based on the results of previous studies or by a preliminary assessment of the factors thought to affect exposure.
2. Estimate exposure variability from pilot tests to help inform the exposure assessment strategy. A similar approach has been suggested by Mathiassen *et al.* (2002) to ensure that laboratory experiments that involve electromyography have adequate power. Pilot testing in the field may require making repeated measurements on multiple workers, work conditions, during different times of the day and on different days. Random-effects ANOVA can then be used to determine the most important sources of exposure variability that need to be considered in the assessment.
3. Once the important sources of exposure variability are identified, develop a sampling strategy that covers, to the extent possible, the different conditions of variables thought to have the greatest impact on exposure variability. When exposures are thought to vary greatly from day to day as in this study, it may be necessary to collect samples on ten or more days.
4. Strategies to assess multiple exposures such as those observed with PATH on groups of workers should be designed conservatively (i.e. observation periods of at least 6 – 10 d) to obtain reliable estimates for all variables. A more efficient approach might involve dropping variables showing low variability in the evaluation after several days of observation; this would, of course, require additional data analysis during the collection of the data. Another similar approach described by van der Beek *et al.*

(1995) involves determining the number of observations needed for each task based on the variability of exposure within task, which is quite useful when one exposure variable is of interest.

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References

Boleij, J., Buringh, E., Heederik, D. and Kromhout, H., 1995, *Occupational Hygiene of Chemical and Biological Agents*, pp. 161–205 (Amsterdam: Elsevier).

Buchholz, B., Paquet, V., Punnett, L., Lee, D. and Moir, S., 1996, PATH: a work sampling-based approach to ergonomics job analysis for construction and other non-repetitive work. *Applied Ergonomics*, **27,** 177–187.

Burdorf, A., 1992, Sources of variance in exposure to postural load on the back in occupational groups. *Scandinavian Journal of Work, Environment and Health*, **18,** 361–367.

Burdorf, A., 1993, Bias in risk estimates from variability of exposure to postural load on the back in occupational groups. *Scandinavian Journal of Work, Environment and Health*, **19,** 50–54.

Burdorf, A., 1995, Reducing random measurement error in assessing postural load on the back in epidemiologic surveys. *Scandinavian Journal of Work, Environment and Health*, **21,** 15–23.

Burdorf, A. and Van Riel, M., 1996, Design strategies to assess lumbar posture during work. *International Journal of Industrial Ergonomics*, **18,** 239–249.

Burdorf, A., Verburgh, A. and Elders, L., 1994, Time-dependent variation in back load of workers in a dairy factory. *Occupational Hygiene*, **1,** 199–206.

Drury, C.G., Paramore, B., Van Cott, H.P., Grey, S.M. and Corlett, E.N., 1987, Task analysis. In *Handbook of Human Factors*, G. Salvendy (Ed.), pp. 370–401 (New York: Wiley).

Hagberg, M., 1992, Exposure variables in ergonomic epidemiology. *American Journal of Industrial Medicine*, **21,** 91–100.

Hansen, D. and Whitehead, L., 1988, The influence of task and location on solvent exposures in a printing plant. *American Industrial Hygiene Journal*, **49,** 259–265.

Hoozemans, M.J.M., Burdorf, A., Van der Beek, A.J., Frings-Dresen, M.H.W. and Mathiassen, S.E., 2001, Group-based measurement strategies in exposure assessment explored by bootstrapping. *Scandinavian Journal of Work Environment and Health*, **27,** 125–132.

Karhu, O., Hansi, P. and Kuorinka, I., 1977, Correcting working postures in industry: a practical method for analysis. *Applied Ergonomics*, **8,** 199–201.

Kromhout, H. and Heederik, D., 1995, Occupational epidemiology in the rubber industry: implications for exposure variability. *American Journal of Industrial Medicine*, **27,** 171–185.

Kromhout, H., Symanski, E. and Rappaport, S.M., 1993, A comprehensive evaluation of within- and between-worker components of occupational exposure to chemical agents. *Annals of Occupational Hygiene*, **37,** 253–270.

Lindman, H., 1974, *Analysis of Variance in Complex Experimental Designs*. (San Francisco, CA: Freeman).

Mathiassen, S.E., Burdorf, A. and Van der Beek, A.J., 2002, Statistical power and measurement allocation in ergonomic intervention studies assessing upper trapezius EMG amplitude: A case study of assembly work. *Journal of Electromyography and Kinesiology*, **32,** 45–57.

Mathiassen, S.E., Moller, T. and Forsman, M., 2003, Variability in mechanical exposure within and between individuals performing a highly constrained industrial work task. *Ergonomics*, **46,** 800–824.

Moir, S.M., Paquet, V., Punnett, L. and Buchholz, B., 2003, Making sense of highway construction: a taxonomic framework for ergonomic exposure assessment and intervention research. *Applied Occupational and Environmental Hygiene*, **18,** 256 – 267.

Moller, T., Mathiassen, S.E., Franzon, H. and Kihlberg, S., 2004, Job enlargement and mechanical exposure variability in cyclic assembly work. *Ergonomics*, **47,** 19 – 40.

Mooney, C. and Duval, R., 1993, *Bootstrapping: A Nonparametric Approach to Statistical Inference*. Sage University Paper series on Quantitative Applications in the Social Sciences, 07–095 (Newbury Park, CA: Sage).

Paquet, V., Punnett, L. and Buchholz, B., 1999, An evaluation of manual materials handling in highway construction work. *International Journal of Industrial Ergonomics*, **24,** 431 – 444.

Paquet, V., Punnett, L. and Buchholz, B., 2001, Validity of fixed-interval observations for postural assessment in construction work. *Applied Ergonomics*, **32,** 215 – 224.

Preller, L., Kromhout, H., Heederik, D. and Tielen, M.J., 1995, Modeling long-term average exposure in occupational exposure-response analysis. *Scandinavian Journal of Work Environment and Health*, **21,** 504 – 512.

Rappaport, S.M., 1991, Assessment of long-term exposures to toxic substances in air. *Annals of Occupational Hygiene*, **35,** 61 – 121.

Rappaport, S.M., Kromhout, H. and Symanski, E., 1993, Variation in exposure between workers in homogeneous exposure groups. *American Industrial Hygiene Association Journal*, **54,** 654 – 662.

Smith, R.W., Sahl, J.D., Kelsh, M.A. and Zalinski, J., 1997, Task-based exposure assessment: analytical strategies for summarizing data by occupational groups. *American Industrial Hygiene Association Journal*, **58,** 402 – 412.

Stammers R.B. and Shepherd, A., 1995, Task analysis. In *Evaluation of Human Work: A Practical Ergonomics Methodology*, second edition, J. Wilson and E.N. Corlett (Eds.), pp. 144 – 168 (London: Taylor & Francis).

Stata Corporation, 1997, *STATA Statistical/Data Analysis*, version 5.0 (College Station, TX: Stata Corporation).

Statistical Analysis System Institute Inc., 1992, *Statistical Analysis System*, version 6 (Cary, NC: SAS Institute, Inc.).

Van der Beek, A.J., Hoozemans, M.J.M., Frings-Dresen, M.H.W. and Burdorf, A., 1999, Assessment of exposure to pushing and pulling in epidemiological field studies: an overview of methods, exposure measures, and measurement strategies. *International Journal of Industrial Ergonomics*, **24,** 417 – 429.

Van der Beek, A.J., Van Gaalen, L.C. and Frings-Dresen, M.H.W., 1992, Working postures and activities of lorry drivers: a reliability study of on-site observation and recording on a pocket computer. *Applied Ergonomics*, **23,** 331 – 336.

Van der Beek, A.J., Kuiper, J.I., Dawson, M., Burdorf, A., Bongers, P.M. and Frings-Dresen, M.H.W., 1995, Sources of variance in exposure to non-neutral trunk postures in varying work situations. *Scandinavian Journal of Work, Environment and Health*, **21,** 215 – 222.

Winkel, J. and Mathiassen, S.E., 1994, Assessment of physical work load in epidemiologic studies: concepts, issues and operational considerations. *Ergonomics*, **37,** 979 – 988.

Woskie, S., Smith, T., Hammond, K. and Hallock, M., 1994, Factors affecting worker exposures to metal-working fluids during automotive component manufacturing. *Applied Occupational and Environmental Hygiene*, **9,** 612 – 621.