DEVELOPING RELIABLE ERGONOMIC EXPOSURE ASSESSMENT STRATEGIES FOR CONSTRUCTION WORK

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The objective of this research was to provide guidelines for the reliable assessment of ergonomic exposures in construction work. Using a modified work-sampling approach, two or three observers collected a total of 4852 observations on tasks performed by three trades (iron workers, carpenters and laborers) for periods of several weeks. At each observation, recorded exposure variables included non-neutral trunk posture, trunk flexion, lateral bending or torsion, arm(s) at or above shoulder height, kneeling, squatting or leg bending, load handling, manual materials handling, hand-tool use and power-tool use. The frequency of exposure was calculated for each worker during each of the tasks on each of the days. ANOVA was used to assess the importance of task, between-worker variability and within-worker variability on exposures across days. A statistical resampling method (bootstrap) was then used to evaluate the reliability of exposure estimates for groups of workers performing the same task for different sampling periods. Most ergonomic exposures were found to vary significantly among construction tasks. In most cases, the between-worker component of variance within task was overshadowed by a large within-worker component of variance thought to consist largely of day-to-day differences in exposure and measurement error. When the average frequency of the ergonomic exposures was bootstrapped, the reliability of the most variable exposures tended to improve as the assessment periods approached 5 to 6 days, with marginal improvements for assessment periods longer than 6 days. Reliable estimates for the least variable exposures were obtained with 1or 2 days of observation. Based on this study, a task-based approach for classifying ergonomic exposures may benefit epidemiologic research and the evaluation of controls in construction work. A preliminary analysis of exposure variability is recommended when determining sampling strategies, and when multiple exposures are assessed simultaneously, sampling periods exceeding 6 days may be required for reliable measures.

INTRODUCTION

Although job title is a common surrogate for exposure in epidemiologic studies (Burdorf, 1993; Hagberg, 1992) and, in practice, ergonomic exposures are often evaluated at the occupational level, it is recognized that characterizing exposures for individuals over a time period thought representative of the work activities will greatly improve the quality of the exposure information needed for epidemiologic research and will provide more detailed information necessary for the evaluation of controls. Unfortunately, multiple workers over long mesaurment periods may be necesary for reliable measures of exposures for jobs that require a variety of work tasks and working situations. 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-repetitive work (e.g., Karhu et al., 1977; van der Beek et al., 1992; Buchholz et al., 1996). While these methods have been used extensively to measure the physical requirements for different occupations or job tasks performed by an occupation, very little attention has been given to the actual number of workers and amount of observation time needed for a reliable estimate of group exposure that can be generalized to other workers performing the same job tasks within a given occupation.

Obtaining reliable measures of group and individual exposure requires knowledge about how exposures vary over time and among workers within a particular group. What is known about how ergonomic exposures are distributed among workers and over time has been generally restricted to the study of postural load on the back for relatively few occupations (e.g., Burdorf et al., 1994; van der Beek et al., 1995; Burdorf, 1995; Burdorf and van Riel, 1996). In construction, the distribution of tasks performed by individuals of a particular trade is highly variable. The dynamic environmental conditions, as well as differences among individuals (e.g., work methods and anthropometry), are additional potential sources of exposure variability. The objective of this research was to provide guidelines for the reliable assessment of different types of ergonomic exposures in construction work.

METHODS

Study Site, Population and Tasks Performed

The study site was a large highway and tunnel construction project located in Boston, MA. This project is a multi-billion dollar effort to build a tunnel under Boston Harbor and depress several miles of interstate highway underneath the city. It involves many contractors and subcontractors and thousands of construction workers over the course of the project. Iron workers, laborers and carpenters were selected because together they represented approximately half of the total work force on the project. Each trade was employed by different contractors and worked on different site locations.

In highway construction, iron workers are responsible for placing and connecting steel rods (rebar) that reinforce concrete structures (e.g., roadway bases, bridges, ramps and tunnels), carpenters construct the forms needed for concrete structures, and laborers perform a variety of support tasks which included pouring concrete, erecting scaffolding, housekeeping, stripping forms, and manually excavating and fortifying shafts and tunnels.

The evaluation was performed on iron workers reinforcing concrete, laborers assisting with the construction of a utility shaft and carpenters building and erecting forms. Data for each trade were collected separately.

Data Collection

PATH (Buchholz et al., 1996) was used to characterize ergonomic exposures for the tasks of each operation. Observations are made in real-time at fixed, short intervals. At each observation, the observers coded the task, body postures, activities, loads handled and tool used (if any) for a single worker, in a checklist type format.

Observations were made repeatedly on crews of workers over periods of several days or weeks. Two or three observers collected PATH data on workers in each of the trades. At the beginning of a day's data collection, each observer selected a crew of 4 to 10 workers to follow for sampling periods of 3 to 4 hours. The iron workers and carpenters were sampled in a random sequence within crews throughout each sampling period. For the laborers, each observer randomly selected a single worker to observe for the day. With both approaches, observations were made at fixed 45 or 60 second intervals. Each operation was observed for 10 to 15 days over a period of 4 to 5 weeks. Prior to formal data collection, PATH coders spent 2 to 3 days observing each operation, piloting the PATH data collection and checking inter-observer reliability of coding.

For the iron workers, a total of 1790 observations were made on three tasks (ground-level rebar construction, wall-rebar construction and preparation work), with 15 to 17 workers observed performing each task on 10 to 13 days. For the laborers, 3219 observations were made on 4 tasks (top work, manual excavation, pit-wall construction and miscellaneous work), with 7 to 10 workers and 9 to 13 days of observation for each task. Eight hundred forty-three observations were made on three carpentry tasks (building forms in a carpentry shop, building forms in the field and erecting forms), for which 4 to 8 workers were observed performing each of the tasks over 6 to 8 days.

Exposure Variables

For each of the 10 tasks, nine exposure variables were evaluated:

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

The frequency of exposure was the percentage of time that an exposure was observed during a day, calculated as the ratio of the number of observations with the exposure to the total number of observations for a worker or group of workers in one day of observation.

Data Analysis

Data management. Data for all operations were scanned into a personal computer using optical mark recognition software (Remark Office OMR, Principia Products, West Chester, PA). The data were visually reviewed for scanning errors and corrected as necessary by manual data entry. The data were analyzed with the Statistical Analysis System (SAS) for the PC (SAS Institute, 1992). Missing data were excluded from the analysis. The exposure frequency (estimated percent of working time exposed) was calculated for each worker on each day of observation for each of the tasks observed. Only daily task-specific exposure frequency estimates based on at least 10 observations and multiple days for each worker were used in the analysis of sources of variance.

Exposure variability due to task within operation. A mixed-effects analysis of variance (ANOVA), treating the tasks performed by the trade within each operation as a fixed-effect parameter and the worker as the random-effect parameter (covariance parameter), was used to determine if exposures varied significantly among tasks. The F-statistic was used to test whether differences in mean exposure existed for the tasks within each operation.

Between-worker and within-worker components of variance within task. For each task, the components of variance were calculated with a random effects ANOVA treating worker as a random effect. The percent of total variance attributed among workers and within workers was then calculated from the variance produced by the random-effects model. The between-worker variance represented differences in average exposure frequency among individual workers. The within-worker variance component was interpreted to be largely attributed to day-to-day differences in exposure, although measurement error was also reflected in this component of variance.

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. While there is no one best computational method for estimating variance components in all situations, the REML method appears to be favored over other methods for estimating the components of variance in crossed-unbalanced designs (Lindman, 1974).

Bootstrapping to evaluate the number of days needed for reliable exposure assessment. The primary aim of the third analysis was to determine the least number of observation days needed to reliably characterize different exposures for groups of workers performing the same task.

The mean daily exposure for each exposure-task combination was calculated using aggregate data from all workers and days studied. The mean daily exposures were calculated with observational data for all workers performing the same task on a day. Only estimates of exposure for tasks based on at least 40 per day observations (across all workers in a task) were included in the analyses.

The bootstrap procedure was used to simulate the obtained daily-group estimates of exposure for assessment periods of one day up to the total number of days in each data set, using Stata software (Stata Corporation, 1997). Bootstrapping is similar to Monte Carlo sampling for which the population distribution is sampled repeatedly to estimate the distribution of a statistic. For each simulated observation period, 1000 samples were drawn with replacement from the empirical distribution of the original sample. Each sample drawn had the same number of values as days in the observation period and the mean value (mean-daily exposure) was calculated for each. The mean and upper and lower boundaries of the 95% confidence interval were plotted against the different assessment periods for each exposure. Differences in the confidence intervals of the exposure estimates for the different observation periods were evaluated qualitatively but not tested statistically.

RESULTS

Exposure Variability among Tasks

There were often large differences in exposure frequency among the tasks performed by each of the trades. For the iron workers, there were statistically significant differences in exposure frequency among tasks for 6 of the 9 ergonomic variables tested; these included any non-neutral trunk posture, trunk flexion, kneeling, squatting or leg bending, hand-tool and power tool use, and MMH ($p<0.01$). Significant differences in exposure frequency among the laborers' tasks ($p<0.01$) were found for 6 of the 9 variables, 5 of which were found statistically significant in the analysis of the iron workers' tasks. There were similar differences in exposure frequency among carpentry tasks for 4 of the 9 exposure variables.

Between-Worker and Within-Worker Components of Variance Within Task

The between-worker component of exposure variance was generally quite small for the tasks performed by the iron workers and the laborers. The between-worker component of exposure variance was less than 10% of the total exposure variance for almost all of the exposures within each of their tasks and exceeded the within-worker variability only in a few cases. For the most part, very little exposure variance was explained by differences among workers for the carpenters' 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.

Evaluation of Number of Observation Days for Reliable Exposure Assessment

There were 6 construction tasks (3 for iron workers, 2 for laborers and 1 for carpenters) that had at least 40 observations on multiple workers each day for multiple days. For the exposures in these tasks, the reliability of the exposure estimates generally increased with increasing observation periods. This effect was most dramatic for the high-frequency high-variability conditions and least dramatic in the low-frequency low-variability conditions.

The bootstrap results for four exposure variables representing the extremes in terms of frequency and between-day variability (i.e., high frequency-high variability, high frequency-low variability, low frequency-high variability; low frequency-low variability) are reported here. The variables were kneeling, squatting or leg bending during the laborers' task manual excavation (high frequency, high variability), trunk flexion during the iron worker's task of ground-level rebar construction (high frequency, low variability), MMH during the laborer's task of pit-wall construction (low frequency, high variability) and power-tool used during ground-level rebar construction (low frequency, low variability).

For the high exposure frequency-high between day exposure variability case, the bootstrap revealed extremely wide confidence intervals for observation periods of 1 to 3 days with dramatic improvements in reliability as assessment periods increased from 1 day ($\pm$ 30%, 95% Confidence Level) to 5 days ($\pm$15%, 95% Confidence Level). The confidence interval decreased very little for observation periods exceeding 6 days. For the high exposure frequency-low exposure variability case, a precision of $\pm$15% (95% Confidence Level) in the exposure frequency estimate was obtained for assessment periods of 1 and 2 days of observation, with a narrowing to $\pm$ 8% for assessment periods of 6 days. This was smaller than that obtained after 10 days of assessment for the high-frequency high-variability exposure. The level of precision achieved for the low exposure frequency-high exposure variability case was fairly good. The level of precision was $\pm$ 4% (95% Confidence Level) for observation periods of 1 day and were $\pm$2% for observation periods of 7 days. As expected, the 95% confidence interval was quite narrow for the low exposure frequency-low exposure variability case, having a precision level of $\pm$ 1% for exposure assessment periods of 1 day with very little change with increasing days of observation.

DISCUSSION

Statistically significant differences in exposure frequency among tasks were found in over one-half of the tests for the three trades evaluated in this study. This was often in spite of both a lack of precision in the measurement of workers' daily exposure frequencies (due to a small number of observations) and a small number of measures for each of the tasks within an operation. Additionally, in this study a trade's tasks were not specifically defined in such a way as to maximize the differences in ergonomic exposures between tasks. It would be nearly impossible to define homogeneous exposure groups in such a way as to maximize the contrast of exposure among groups for all of the different ergonomic exposures studied here. Instead, tasks were defined operationally so that the task definitions could be easily understood by contractors and workers, as well as those who made PATH observations. Nevertheless, the large difference in exposure frequencies among tasks observed here provides evidence supporting the task-based strategy as a viable way to enhance the characterization of exposure for groups, as well as to allow the level of detail needed for the evaluation of ergonomic controls for work tasks.

In this study, the between-worker exposure variance within task was often found to be quite small when compared to the within-worker variance component. This may suggest that the task-specific exposures for workers may often be similar over time for all workers performing the same task and further supports the classification of exposures by tasks rather than by trade. However, in this study the daily task-based exposure frequency estimates for workers were often based on a small number of observations. The lack of precision in these exposure measurements may have, in some cases, inflated the within-worker exposure variance and deflated the true estimate of exposure explained by the effect of worker.

The need to perform assessments on multiple days for reliable exposure estimates for exposures with high inter-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 and illustrated the importance of evaluating ergonomic exposures for groups of workers on multiple days to improve the reliability of the exposure when exposure frequencies are high and variable. The most important limitation of the bootstrap approach used here 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). The bootstrap approach used in this study, when applied to larger data sets could be used to develop long-term exposure assessment efforts for epidemiologic research and for the evaluation of controls in highly variable working conditions.

RECOMMENDATIONS

1. A task-based approach should be used to assess ergonomic exposures in highway construction work.
2. Two days of exposure assessment were not sufficient to provide even a preliminary assessment of exposure variability across days. No fewer than 3 or 4 days of exposure data are recommended for an initial estimate of between-day exposure variability for groups of workers.
3. Observation periods of at least 6 to 10 days are recommended when the between-day variability of exposure is high.
4. Strategies for the assessment of multiple exposures (such as those observed with PATH) should be designed conservatively (i.e., observation periods of at least 6 to 10 days) to obtain reliable estimates for all variables. A more efficient approach might involve dropping variables with low frequency and low variability from the evaluation after several days of observation.

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