Applied Ergonomics 42 (2011) 665–671

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Physical ergonomic hazards in highway tunnel construction: Overview from the Construction Occupational Health Program

SangWoo Tak [a,*], Bryan Buchholz [a], Laura Punnett [a], Susan Moir [a,b], Victor Paquet [a,c], Scott Fulmer [a], Helen Marucci-Wellman [a,d], David Wegman [a]

[a] Department of Work Environment, University of Massachusetts Lowell, Lowell, MA 01854, USA
[b] University of Massachusetts Boston, Boston, MA, USA
[c] University at Buffalo, SUNY, 411 Bell Hall, Buffalo, NY 14260-3302, USA
[d] Liberty Mutual Research Institute, Hopkinton MA 01748, USA

A R T I C L E I N F O

Article history:
Received 24 November 2009
Accepted 2 October 2010

Keywords:
PATH
Trade
Operation
Postural load
Highway tunnel construction

A B S T R A C T

This report provides an overview of physical ergonomic exposures in highway construction work across trades and major operations. For each operation, the observational method "PATH" (Posture, Activity, Tools and Handling) was used to estimate the percentage of time that workers spent in specific tasks and with exposure to awkward postures and load handling. The observations were carried out on 73 different days, typically for about 4 h per day, covering 120 construction workers in 5 different trades: laborers, carpenters, ironworkers, plasterers, and tilers. Non-neutral trunk postures (forward or sideways flexion or twisting) were frequently observed, representing over 40% of observations for all trades except laborers (28%). Kneeling and squatting were common in all operations, especially tiling and underground utility relocation work. Handling loads was frequent, especially for plasterers and tilers, with a range of load weights but most often under 15 pounds. The results of this study provide quantitative evidence that workers in highway tunnel construction operations are exposed to ergonomic factors known to present significant health hazards. Numerous opportunities exist for the development and implementation of ergonomic interventions to protect the health and safety of construction workers.

© 2010 Elsevier Ltd and The Ergonomics Society. All rights reserved.

1. Introduction

Construction workers are exposed to a variety of ergonomic hazards, including awkward postures, heavy lifting, forceful exertions, vibrations, and repetitive motions (Schneider and Susi, 1994; Hartmann and Fleischer, 2005). They also experience an elevated risk of musculoskeletal disorders (Latza et al., 2000; O'Reilly et al., 2000; Sandmark et al., 2000; Schneider, 2001; Goldsheyder et al., 2002; Holmstrom and Engholm, 2003; Forde et al., 2005).

Much of the work performed in construction is non-routinized (Buchholz et al., 1996). This is due both to the dynamic nature of construction work itself and the changing external environment, which may impact the content and frequency distribution of job tasks across individuals and over time (Paquet et al., 2005). The dynamic nature of construction work also makes it difficult to measure ergonomic exposures systematically. A few investigators have used observational methods to determine the distribution of ergonomic exposures in specific construction trades or tasks (Wickstrom et al., 1985; Kivi and Mattila, 1991; Bhattacharya et al., 1997; Jensen and Eenberg, 2000). However, there have been few or no large-scale comparisons of exposure to physical ergonomic hazards among different trades or stages of the construction process. The objective of this report is to provide an overview of ergonomic exposures in highway construction work and to describe the frequency of known health hazards by the major trades and operations involved.

2. Methods

2.1. Study site and population

Data were compiled from 9 field studies that were carried out by ergonomists from the Construction Occupational Health Program (COHP) at the University of Massachusetts Lowell during the last decade (Buchholz et al., 1996; Kittusamy and Buchholz, 2001; Paquet et al., 2001; Buchholz et al., 2003; Paquet et al., 2005; Tak et al., 2009). All the studies took place at a very large highway

* Corresponding author. National Institute for Occupational Safety and Health, 4676 Columbia Parkway, R-17, Cincinnati OH 45226, USA. Tel.: +1 513 458 7117; fax: +1 513 841 4489.
E-mail address: STak@cdc.gov (SangWoo Tak).

0003-6870/$ – see front matter © 2010 Elsevier Ltd and The Ergonomics Society. All rights reserved.
doi:10.1016/j.apergo.2010.10.001

construction site in Boston, Massachusetts. The operations were characterized according to a taxonomy that was created based on the Massachusetts Highway Department specifications (Moir et al., 2003). All observed workers were unionized, so the scope of work by each trade followed Massachusetts union jurisdictions. This study has been approved by the Institutional Review Board of the University of Massachusetts Lowell. All construction workers gave their informed consent prior to their inclusion in the study.

2.2. Data Collection

PATH (Posture, Activities, Tools, Handling) incorporates a modified work-sampling approach into observational job analysis. It provides unbiased estimates of the frequency of ergonomic exposures such as tasks, postures and load in the hands, linked to the tasks in which they are performed through concurrent recording of both, over multi-hour observation periods (Buchholz et al., 1996). Based on the Ovako Working Posture Analysis System (OWAS) (Karhu et al., 1977), the posture codes in PATH are defined as ranges of angles; for example, mild trunk flexion is defined as 20–45 of forward bending.

Codes for tasks, activities, and other exposures were developed *de novo*; many were customized to the specific trades following informal observations and discussions with workers and supervisors. Observers were rigorously trained and inter-observer agreement was confirmed before field data were collected.

In each study, we observed a single team of workers performing one operation on multiple days. A series of PATH observations were made at fixed intervals, either 45 or 60 s apart, typically for about 4 h per day. The observations cycled through all workers in the team, so multiple observations were made for each worker present on site each day.

2.3. Description of operations

A total of 9 separate operations were observed. To build concrete structures, ironworkers engaged in *Concrete Reinforcing* are responsible for placing and connecting steel rods (rebar) that reinforce concrete structures on construction sites. Carpenters then build forms around the steel rods (*Concrete Form Building*); the form-building operations are building, erecting and stripping forms. Construction laborers pour concrete into the forms (*Concrete Pouring*). Concrete is poured from a concrete pump truck through a hose. Some laborers use short handled shovels, lutes, or rakes to spread the concrete. Other laborers use large and small trowels to smooth out the concrete. Laborers also perform a variety of support tasks, such as erecting scaffolding, housekeeping, stripping forms, and manually excavating and fortifying shafts and tunnels.

Pipejacking is a common method to install underground piping, sewer lines, and electrical ducts 30 feet below the surface. It is an alternative to the traditional 'excavate, lay, and fill' pipe installation method, used especially when it is very important to minimize disruptions to surrounding activities or structures. Instead of digging deep trenches, two pits—a jacking pit and a receiving pit—are built initially. *Jacking Pit Construction* results in a pit that houses the equipment used to jack pipes through the soil. The pit is usually 30 feet × 30 feet × 30 feet with lagging installed around the sides to prevent the soil from caving in on the tunnelers while they work. After the jacking pit is completed, the pipes are then "jacked" through the soil to the receiving pit. Laborers assist the Tunnelers during both Jacking Pit Construction and Pipe-jacking.

The purpose of *Slurry Wall Construction* is to provide a barrier between a trench and the adjacent earth, to prevent earth from spilling into the trench (caving) and water intrusion. This requires below-grade excavation, through stabilizing slurry, to support the excavation walls. Due to the dangers of trenching and excavating, the use of slurry walls has increased greatly since it was first introduced in 1980's. Laborers perform manual excavation and housekeeping, often by breaking up large clumps of concrete that were not broken down by mixing, or rinsing any clay or slurry back into the trench to avoid slippage on the working surface.

Plastering, *Tiling*, and *Grouting* operations take place in the stage of tunnel wall finishing. During *Plastering*, plasterers apply finish coats of plaster to sections of the tunnel walls. After the first coat of concrete is applied, the "brown coat" is applied the next day on top of the first coat. Tilers then install and grout the tiles on the plastered section. During the *Wall Tiling* operation, tile finishers mix mortar, prepare the tile for setting and prepare the base of the wall for tiling, while tile mechanics are responsible for tile setting and supervising of the operation. In *Grouting*, tile finishers prepare the joints between the tiles, prepare the grout, grout and clean the tiles.

2.4. Data analysis

The proportion of observations for each task was estimated by operation. Exposure measures were computed as the percentage of the total work time accounted for by each exposure, i.e., proportion of time spent in trunk flexion, kneeling and squatting, etc. Descriptive data for trunk, leg and arm postures, and loads handled, were tabulated to provide operation- and trade-specific estimates of the proportion of time that workers were exposed to each ergonomic factor. Observations with missing information on trunk, leg, or arm postures were excluded from the analysis. Chi-square tests were performed to determine whether exposures varied among operations or trades.

3. Results

A total of 15,141 PATH observations were made on 73 days. These observations covered 120 construction workers in 5 different trades performing 9 operations (Table 1). Most operations had more than 5 days of observations except *Slurry Wall* (3 days), whereas four operations, *ConcreteForm Building*, *Concrete Reinforcing*, *Jacking Pit* and *Tiling*, had more than 12 days of observation.

Each operation consisted of at least four or more tasks; usually one or two primary tasks accounted for more than 20% of the total work time (Table 2). Of the 46 tasks observed, most were specific to

Table 1
Highway construction operations and workers observed on Central Artery/Third Harbor Tunnel project, Boston, MA, USA, 1995–2005.

Operation	No of days observed	Trade	No of workers observed	Tasks observed	No of observations
Concrete Form Building	14	Carpenters	15	8	1663
		Laborer	2		
Pipe Jacking	5	Tunneler[a]	3	4	1317
		Laborer	1		
Concrete Pouring	6	Laborer	7	5	743
Concrete Reinforcement	13	Ironworker	17	6	2027
Grouting	7	Tiler	18	5	1564
Jacking Pit	12	Tunneler[a]	1	5	3094
		Laborer	11		
Plastering	8	Plasterer	11	4	1642
Slurry Wall	3	Laborer	13	4	931
Tiling	14	Tiler	21	5	2160
Total	73		120	46	15,141

[a] Tunneler is a subspecialty of laborer, included within Laborers in subsequent tables and figures because of the small number of workers.

Table 2
Tasks observed in highway construction, by operation (all trades combined): Central Artery/Third Harbor Tunnel project, Boston, MA, 1995–2005.

Operation	Task	Number of observations	Percent
Concrete Form Building	Assembly PIF	89	5.4
	Building form	456	27.4
	Erecting form	325	19.5
	House keeping	57	3.4
	Material moving	271	16.3
	Saw/Cut	269	0.7
	Stripping form	11	6.1
	Supervising	101	16.20
	Total[a]	1663	100
Concrete Pouring	Pour concrete	229	31.2
	Preparation	4	0.5
	Smooth concrete	121	16.5
	Spread concrete	187	25.4
	Clean and Misc.	194	26.4
	Total[a]	743	100
Concrete Reinforcing	Caisson	2	0.1
	Horizontal (road)	601	29.7
	Preparation	644	31.8
	Supervising	165	8.1
	Ventilation	168	8.3
	Vertical (wall)	446	22.0
	Total[a]	2027	100
Grouting	Clean	802	51.3
	Grout	343	21.9
	Misc	232	14.8
	Prepare-Grouting	56	3.6
	Prepare-Joint	113	7.23
	Total[a]	1564	100
Pit Jacking	Construct Pit Wall	537	17.4
	Manual Excavation	1365	44.1
	Misc.	522	16.9
	Preparation Work	3	0.1
	Top Work	667	21.6
	Total[a]	3094	100
Pipe Jacking	Bottom Work	409	31.1
	Manual Excavation	528	40.1
	Misc.	9	0.7
	Top work	370	28.1
	Total[a]	1317	100
Plastering	Apply Concrete	226	14.0
	Brown Coating	1051	65.2
	Misc	283	17.6
	Prepare Apply Concrete	52	3.2
	Total[a]	1642	100
Slurry wall	Construct Pit Wall	172	18.4
	Manual Excavation	278	29.9
	Misc	185	19.8
	Top Work	296	31.8
	Total	931	100
Tiling	Ground level	240	11.1
	Supervising	79	3.7
	Tile prepare	770	35.7
	Tile setting	1051	48.7
	Wall base	20	0.9
	Total	2160	100

[a] Total numbers include observations with task missing: 84 (ConcreteForm Building), 8 (Concrete Pouring), 1 (Concrete Reinforcement), 18 (Grouting), 1 (Pipe Jacking), and 30 (Plastering).

individual operations, while a few tasks, such as supervising, were common in multiple operations. Thus, there were 35 unique tasks.

3.1. Trunk postures

Non-neutral trunk postures were frequently observed in almost every operation. *Concrete Form Building*, *Concrete Reinforcement*, *Plastering*, *Grouting*, and *Tiling* each involved non-neutral trunk postures for more than 40% of the work time (Fig. 1). The frequency of non-neutral trunk postures differed significantly across operations. Workers performing *Tiling* were the most exposed to 'flexed and twisted' trunk posture (15%), followed by those doing *Concrete Reinforcement* (14%). Laborers had the least exposure to non-neutral trunk posture (28%).

3.2. Leg postures

The frequency of non-neutral leg postures differed significantly among operations and trades (Fig. 2). The *Jacking Pit* operation presented the highest percentage of 'knees bent' (26%), followed by *Concrete Reinforcement* and *Pipejacking* (17%). Squatting was observed most frequently when tilers were performing *Grouting* (11%). During *ConcreteForm Building*, *Grouting*, and *Tiling*, kneeling was observed in over 7% of work time (Fig. 2). Carpenters spent the least time with 'knees bent' (5%) and the most time in 'walking' (21%).

3.3. Arm postures

The frequency of arm elevation differed significantly among operations and trades (Fig. 3). One or both arms were elevated at or above shoulder height for more than 10% of the time during *Tiling*, *Plastering*, *Grouting* and *Pipejacking* (Fig. 3). Both arms above shoulder height were observed most frequently during *Tiling* (3.5%) and least often during *Slurry Wall Construction* (1.2%).

3.4. Loads handled

The frequencies of load weights varied significantly across operations and trades (Fig. 4). Plasterers handled loads of 5–14.9 lbs for 54% of the time in *Plastering*. Loads of 15–50 lbs were handled frequently in *Concrete Form Building* (11%) and *Pipe Jacking* (23%). Loads exceeding 50 lbs were observed most frequently for ironworkers (5%) and during *Concrete Reinforcement* (4%).

4. Discussion

The construction workers on this major highway and tunnel project had high exposure to multiple ergonomic hazards which are known to represent risk of musculoskeletal disorders to the back, knees, and other joints. The predominant exposure in the operations observed was to awkward postures of the back. Trunk flexion ranged from 35% to 55% of work time, on average, by trade. Squatting and kneeling were uncommon overall but represented more than 10% of work time in certain operations. Construction workers also regularly handled materials or tools. Loads handled in construction vary tremendously in terms of object or tool type, size, and weight. Most of those that we observed weighed less than 15 pounds, but occasional very heavy loads were handled.

The results of this study can be used to target job tasks that are hazardous and thus deserve intervention. Non-neutral postures and work locations, the size and weights of tools and objects handled, and lifting frequency should be considered in order to reduce the hazards associated with highway tunnel construction operations. For example, Concrete Pouring by laborers should be targeted specifically to reduce the frequency of severe trunk flexion. Lower extremity exposures have received little attention to date, with a few exceptions (e.g., Jensen and Eenberg, 2000; Jensen and Mikkelsen, 2000), but may represent important hazards for certain trades or specialties within trades.

Our findings can also be used to evaluate specific interventions for reducing ergonomic exposures among construction workers. For example, the frequency of non-neutral knee postures in workers

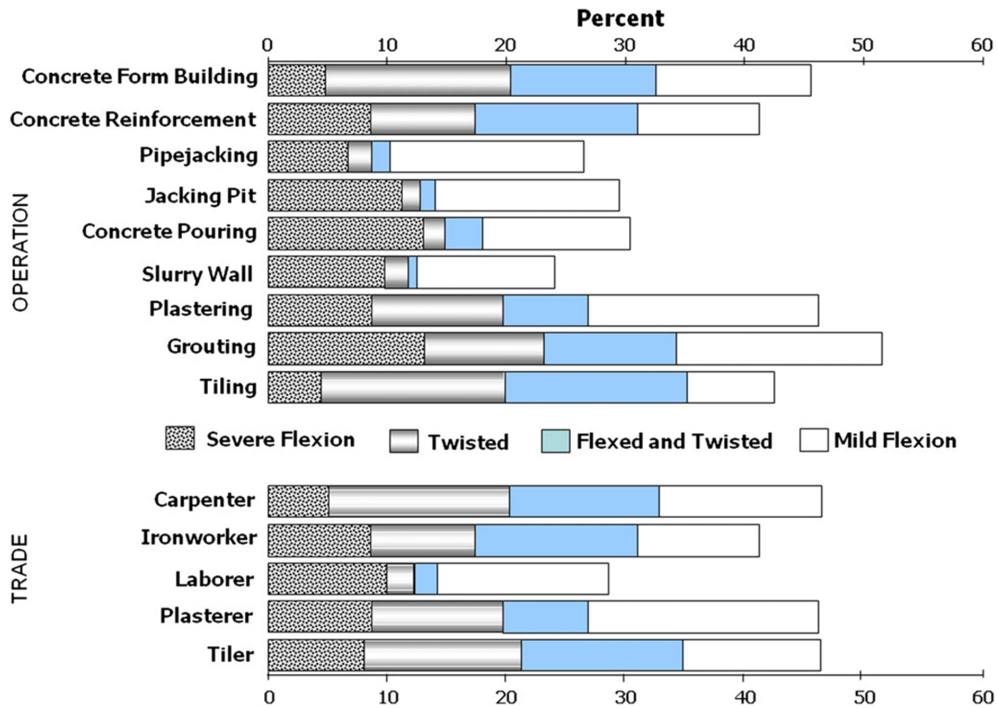

Fig. 1. Distributions of trunk postures (as percentage of all observations) by operations and trades: Central Artery/Third Harbor Tunnel project, Boston, MA, 1995–2005 * Note: chi-square test on operations with 32 d.o.f. ($p < 0.001$) and trades with 16 d.o.f. ($p < 0.001$). All bars are stacked within each category.

performing Tiling and Grouting that we observed could be compared to that in workers performing the same tasks but with different equipment.

The frequency and magnitude of ergonomic exposures in construction tasks have previously been reported (Kivi and Mattila, 1991; Holmstrom et al., 1992; Mattila et al., 1993; Stenlund et al., 1993; Schneider and Susi, 1994; Spielholz et al., 1998; Latza et al., 2000; Latza et al., 2002). However, the scope of the job tasks covered in those studies was usually limited to one or a few trades. In contrast, in COHP we collected data on multiple

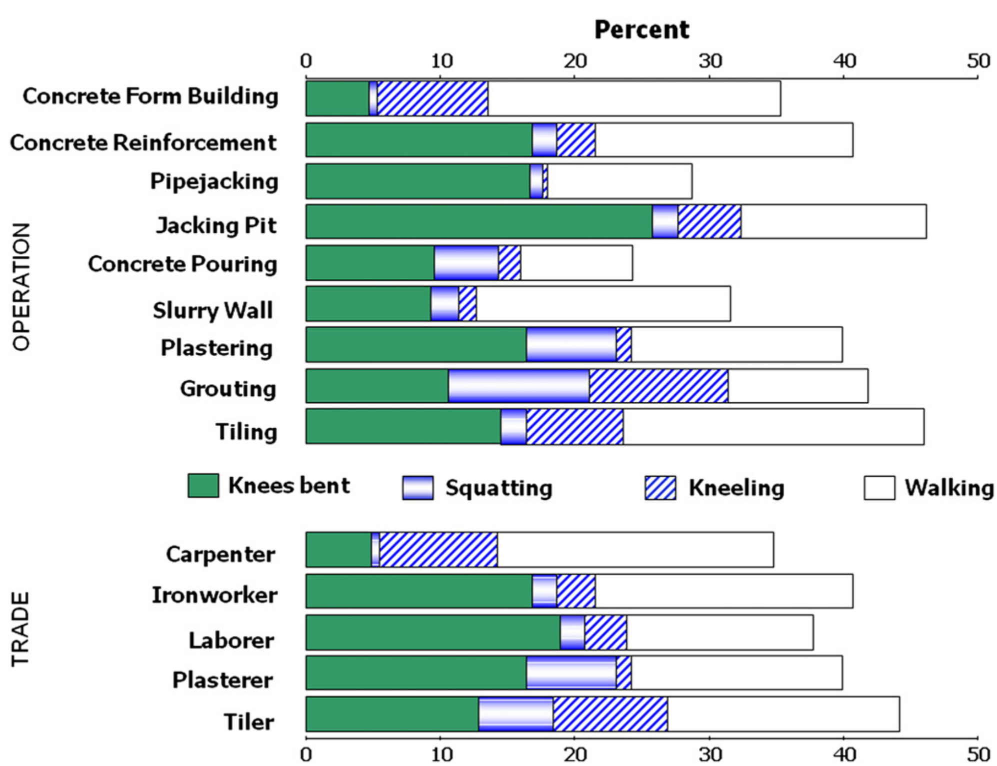

Fig. 2. Distributions of leg postures (as percentage of all observations) by operations and trades: Central Artery/Third Harbor Tunnel project, Boston, MA, 1995–2005 * Note: chi-square test on operations with 24 d.o.f. ($p < 0.001$) and trades with 12 d.o.f. ($p < 0.001$). All bars are stacked within each category.

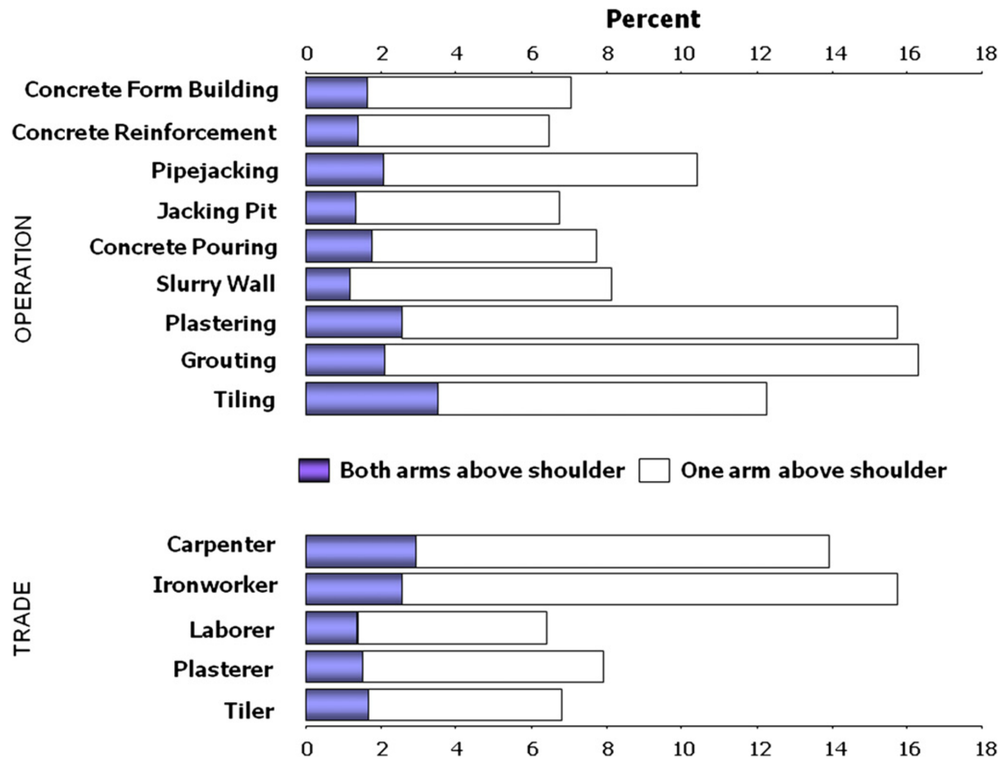

Fig. 3. Distributions of arm postures (as percentage of all observations) by operations and trades: Central Artery/Third Harbor Tunnel project, Boston, MA, 1995–2005 * Note: chi-square test on operations with 16 d.o.f. ($p < 0.001$) and trades with 8 d.o.f. ($p < 0.001$). All bars are stacked within each category.

operations with the same observational procedures and metrics, providing a broader scope of physical ergonomic exposures in heavy construction and permitting the systematic comparison of several trades and operations. Our data also include observed task frequency and task-specific exposures, permitting evaluation of variability by operation and task and facilitating generalizability to other jurisdictions as long as the task content of specific construction trades can be defined.

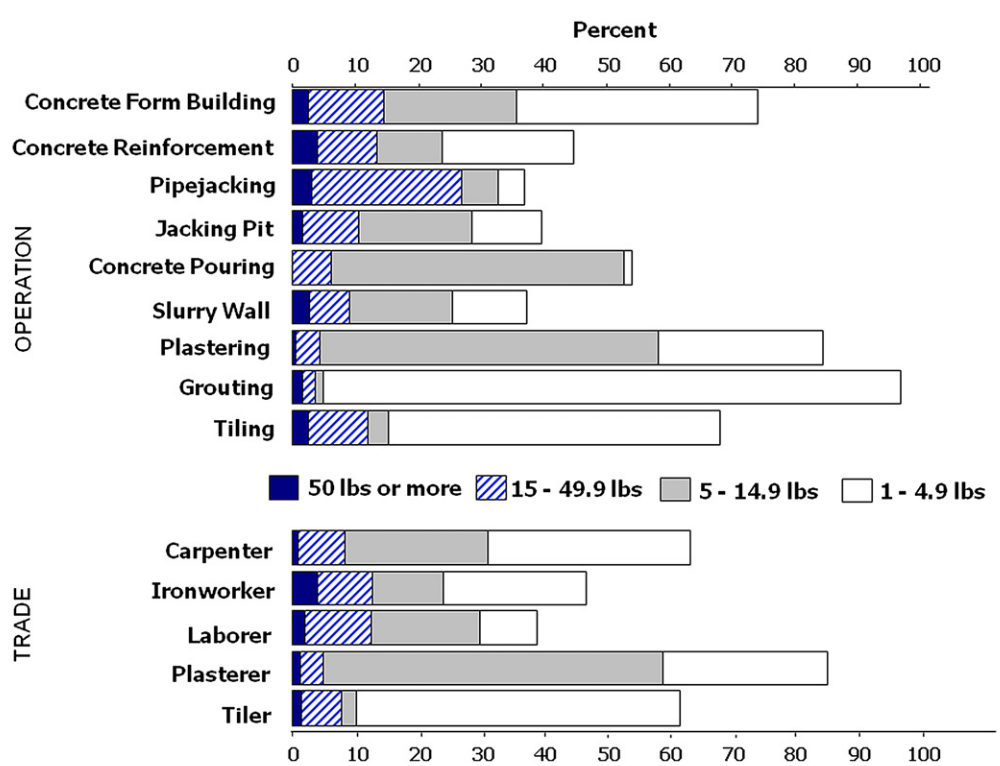

Fig. 4. Distributions of loads handled (as percentage of all observations) in highway tunnel construction by operations and trades: Central Artery/Third Harbor Tunnel project, Boston, MA, 1995–2005 * Note: chi-square test on operations with 24 d.o.f. ($p < 0.001$) and trades with 12 d.o.f. ($p < 0.001$). All bars are stacked within each category.

In addition, many previous studies relied on worker self-report, without any evaluation of validity. While assessment of one's own job demands may be reliable for short periods of time, the highly variable nature of construction work means that long-term recall and mental averaging or other summing processes are required to provide an assessment of exposure for extended periods. To avoid these pitfalls we obtained observational data for both exposures and tasks.

The exposure frequencies obtained for these construction operations are based on the assumption that the selection of time period and workers observed allow both an unbiased and representative estimate of the exposure for each operation. We believe that the estimates are unbiased; dates were selected as a convenience sample and to ensure observation of key tasks in each operation, but without regard to expected exposure frequencies.

Our estimates of ergonomic exposures in this study may not be readily comparable to previous studies due to differences in the methods of measurement and tasks performed, as well as random sampling error. For example, we observed non-neutral knee postures in about 15% of working time for carpenters whereas Jensen and Mikkelsen (2000) reported that knee-straining work postures constituted 27% of working time for carpenters using video-recording method. Nonetheless, both studies indicate high exposures that likely represent high risk for biomechanical strain on carpenters' knees.

The ergonomic exposures measured in the present study might not be perfectly representative, in that we may have missed infrequent tasks and because conditions in construction work change rapidly due to a variety of factors, such as different project settings, equipment or tool use and weather (Tak et al., 2009). For example, the increasing height of a wall being built over the course of a day would likely require work with more overhead reaching, or on a higher scaffold with more stooping, later in the day. If the assessments were not made on a representative sample of workers, or when members of these groups do not, in fact, have similar exposures, or if we missed important conditions or tasks for any trade, these data might not be generalizable to other settings. Our measurements were made on fairly large groups of workers over periods of several weeks. However, measurements were not made on all possible environmental conditions that construction workers might experience while performing the tasks; cold weather and night work in particular were probably under-represented. We do not know whether these conditions would affect work postures or load handled, but if they do the exposure values reported here might not apply.

Nevertheless, anecdotal information from construction workers, foremen, and safety supervisors indicated that the jobs and the exposures described in this study are indeed common in construction. Hence, future epidemiologic and intervention studies could benefit from the highly detailed exposure assessments that we have obtained.

PATH provides quantitative information about the percent of time spent in specific body postures, and activities, such as load handling. There are several potential limitations related to the use of PATH or any other observational methods. The amount of dynamic work may affect the reliability of observations of posture (Burdorf et al., 1992; Leskinen et al., 1997; Park et al., 2009). Most of the operations in this study required the subjects to change posture frequently; rapid motions could easily introduce measurement error. The accuracy of the observations is also likely dependent on the expertise and experience of the observer (Park et al., 2009). In this study we used well-trained observers, all graduate students in occupational ergonomics. We evaluated observer reliability and validity on multiple occasions and the results were consistently favorable (Buchholz et al., 1996; Paquet et al., 1999; Paquet et al., 2001; Park et al., 2009).

5. Conclusion

In this study of a large highway tunnel construction project, multiple ergonomic exposures were observed. The most frequent exposures were non-neutral trunk postures and, in some operations, kneeling and squatting. These exposures have already been demonstrated to represent important risk of musculoskeletal disorders, particularly affecting the back and knees (Jensen and Mikkelsen, 2000; National Research Council, 2001; Manninen et al., 2002). Each construction trade presents different ergonomic challenges. Therefore, obtaining trade and operation-specific information on tools, exposures, worker tasks, and work conditions is an important first step in: 1) comparing risks, 2) identifying priorities for reduction of hazardous ergonomic exposures, and 3) determining the most appropriate intervention measures for each trade.

Acknowledgment

The Center to Protect Workers' Rights (CPWR) supported this research with grants provided by the National Institute for Occupational Safety and Health (NIOSH) (grants #U02/CCU308771, U02/CCU312014, and U02/CCU317202). Its contents are solely the responsibility of the authors and do not necessarily represent the official views of NIOSH or CPWR. The authors are grateful for the cooperation of many construction workers who answered our questions and permitted us to observe their daily work. The data tables with detailed information will be shared upon request from any interested readers.

References

Bhattacharya, A., Greathouse, L., et al., 1997. An ergonomic walkthrough observation of carpentry tasks: a pilot study. Appl. Occup. Environ. Hyg. 12 (4), 278–287.
Buchholz, B., Paquet, V., et al., 1996. PATH: a work sampling-based approach to ergonomic job analysis for construction and other non-repetitive work. Appl. Ergon. 27 (3), 177–187.
Buchholz, B., Paquet, V., et al., 2003. Quantification of ergonomic hazards for ironworkers performing concrete reinforcement tasks during heavy highway construction. AIHA J. (Fairfax, Va). 64 (2), 243–250.
Burdorf, A., Derksen, J., et al., 1992. Measurement of trunk bending during work by direct observation and continuous measurement. Appl. Ergon. 23 (4), 263–267.
Forde, M.S., Punnett, L., et al., 2005. Prevalence of musculoskeletal disorders in union ironworkers. J. Occup. Environ. Hyg. 2 (4), 203–212.
Goldsheyder, D., Nordin, M., et al., 2002. Musculoskeletal symptom survey among mason tenders. Am. J. Ind. Med. 42 (5), 384–396.
Hartmann, B., Fleischer, A.G., 2005. Physical load exposure at construction sites. Scand. J. Work Environ. Health 31 (Suppl 2), 88–95.
Holmstrom, E., Engholm, G., 2003. Musculoskeletal disorders in relation to age and occupation in Swedish construction workers. Am. J. Ind. Med. 44 (4), 377–384.
Holmstrom, E.B., Lindell, J., et al., 1992. Low back and neck/shoulder pain in construction workers: occupational workload and psychosocial risk factors. Part 1: relationship to low back pain. Spine 17 (6), 663–671.
Jensen, L.K., Eenberg, W., et al., 2000. Validity of self-reporting and video-recording for measuring knee-straining work postures. Ergonomics 43 (3), 310–316.
Jensen, L.K., Mikkelsen, S., et al., 2000. Work-related knee disorders in floor layers and carpenters. J. Occup. Environ. Med. 42 (8), 835–842.
Karhu, O., Kansi, P., et al., 1977. Correcting working postures in industry: a practical method for analysis. Applied Ergon. 8 (4), 199–201.
Kittusamy, N.K., Buchholz, B., 2001. An ergonomic evaluation of excavating operations: a pilot study. Appl. Occup. Environ. Hyg. 16 (7), 723–726.
Kivi, P., Mattila, M., 1991. Analysis and improvement of work postures in the building industry: application of the computerised OWAS method. Appl. Ergon. 22 (1), 43–48.
Latza, U., Karmaus, W., et al., 2000. Cohort study of occupational risk factors of low back pain in construction workers. Occup. Environ. Med. 57 (1), 28–34.
Latza, U., Pfahlberg, A., et al., 2002. Impact of repetitive manual materials handling and psychosocial work factors on the future prevalence of chronic low-back pain among construction workers. Scand. J. Work Environ. Health 28 (5), 314–323.
Leskinen, T., Hall, C., et al., 1997. Validation of Portable Ergonomic Observation (PEO) method using optoelectronic and video recordings. Appl. Ergon. 28 (2), 75–83.
Manninen, P., Heliovaara, M., et al., 2002. Physical workload and the risk of severe knee osteoarthritis. Scand. J. Work Environ. Health 28 (1), 25–32.

Mattila, M., Karwowski, W., et al., 1993. Analysis of working postures in hammering tasks on building construction sites using the Computerized OWAS method. Appl. Ergon. 24 (6), 405–412.
Moir, S., Paquet, V., et al., 2003. Making sense of highway construction: a taxonomic framework for ergonomic exposure assessment and intervention research. Appl. Occup. Environ. Hyg. 18 (4), 256–267.
National Research Council, 2001. Musculoskeletal Disorders and the Workplace: Low Back and Upper Extremities. Panel on Musculoskeletal Disorders and the Workplace. National Academy Press, Washington, DC.
O'Reilly, S.C., Muir, K.R., et al., 2000. Occupation and knee pain: a community study. Osteoarthritis Cartilage 8 (2), 78–81.
Paquet, V., Punnett, L., et al., 1999. An evaluation of manual materials handling in highway construction work. Int. J. Ind. Ergon., 431–444.
Paquet, V., Punnett, L., et al., 2005. Reliable exposure assessment strategies for physical ergonomics stressors in construction and other non-routinized work. Ergonomics 48 (9), 1200–1219.
Paquet, V.L., Punnett, L., et al., 2001. Validity of fixed-interval observations for postural assessment in construction work. Appl. Ergon. 32 (3), 215–224.
Park, J.K., Boyer, J., et al., 2009. Inter-rater reliability of PATH observations for assessment of ergonomic risk factors in hospital work. Ergonomics 52 (7), 820–829.
Sandmark, H., Hogstedt, C., et al., 2000. Primary osteoarthrosis of the knee in men and women as a result of lifelong physical load from work. Scand. J. Work Environ. Health 26 (1), 20–25.
Schneider, S., Susi, P., 1994. Ergonomics and construction: a review of potential hazards in new construction. Am. Ind. Hyg. Assoc. J. 55 (7), 635–649.
Schneider, S.P., 2001. Musculoskeletal injuries in construction: a review of the literature. Appl. Occup. Environ. Hyg. 16 (11), 1056–1064.
Spielholz, P., Wiker, S.F., et al., 1998. An ergonomic characterization of work in concrete form construction. Am. Ind. Hyg. Assoc. J. 59 (9), 629–635.
Stenlund, B., Goldie, I., et al., 1993. Shoulder tendinitis and its realtion to heavy manual work and exposure to vibration. Scand. J. Work Environ. Health 19, 43–49.
Tak, S., Paquet, V., et al., 2009. Variability in risk factors for knee injury in construction. J. Occup. Environ. Hyg. 6 (2), 113–120.
Wickstrom, G., Niskanen, T., et al., 1985. Strain on the back in concrete reinforcement work. Br. J. Ind. Med. 42, 233–239.