THE ASSESSMENT OF ERGONOMIC EXPOSURES IN CONSTRUCTION WORK

BY

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ABSTRACT OF A DISSERTATION SUBMITTED TO THE FACULTY OF
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ABSTRACT

The objectives of this research were to evaluate the validity of real-time observational assessment of body postures and to provide information needed for improving ergonomic exposure assessment strategies in construction work.

The first study involved the development and evaluation of an electronic direct postural measurement system designed to measure shoulder, knee and trunk postures. In a laboratory study on 5 subjects, the electronic inclinometers predicted shoulder, trunk and knee flexion to within 5 to 10 degrees of accuracy and the lumbar motion monitor (LMM) predicted trunk lateral bending and torsion to within 3 degrees of accuracy with no or very simple calibration procedures.

The second study involved the evaluation of discrete-interval observations for the assessment of body postures during construction tasks, by comparing categories of body posture recorded with two work-sampling approaches (PATH and a simplified version of PATH) to measurements obtained with the electronic postural assessment system and video analysis. Five subjects were each observed performing 3 of 6 simulated construction tasks. Overall, agreement among the work-sampling and the electronic methods was high, although there were some notable differences in the measured frequency of some leg and trunk postures.

The third study involved the evaluation of the efficacy of the task-based assessment approach through the examination of between-worker and within-worker components of exposure variability in a sample of construction tasks. In addition, bootstrapping (a computer resampling technique) was used to evaluate how the number of days of assessment affected the reliability of the exposure measure for groups of workers

performing the same task. Exposures often varied greatly among tasks of a construction operation, indicating that the task-based approach is useful to improve precision in exposure assessment. The between-worker component of exposure variability, for the most part, was much smaller than the within-worker exposure variability over several days, supporting the hypothesis of high day-to-day exposure variability during construction work. Bootstrapping revealed that low frequency exposure variables may require as few as 1 or 2 days of assessment (particularly for low-variability exposures), while exposures with higher frequency may require 6 or more days (particularly for high-variability exposures) to allow a reliable assessment of exposure frequencies for construction tasks.

This research demonstrates how work sampling approaches can be used to obtain valid and reliable measurements of ergonomic exposures. The results have implications for both the evaluation of control measures in the work place and for exposure assessment in epidemiologic studies.

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CHAPTER I. INTRODUCTION

A. OBJECTIVE AND SPECIFIC AIMS

The objective of the research was to evaluate an observational method for the assessment of body postures and to provide information needed to guide exposure assessment strategies for measurement of ergonomic exposures in construction work. Over the past five years, the Department of Work Environment's Construction Occupational Health Project (COHP) at the University of Massachusetts Lowell has developed and used a work sampling-based exposure assessment technique known as PATH (Posture, Activities, Tools and Handling). PATH was designed to provide information about the frequency of ergonomic exposures (measured as the percentage of time exposed) in construction work; more recently this method has also been used in agriculture and retail facilities. COHP has used PATH to quantify the frequency of ergonomic hazards in tasks performed by construction laborers, carpenters, iron workers, tilers and plasterers in highway construction. To date, PATH exposure assessment efforts have been limited in at least two ways: 1) the validity of PATH's assessment of body postures has not been sufficiently evaluated, and 2) exposure assessment efforts (i.e., the number of observations per worker and the total number of days and workers observed) have been driven by logistical considerations rather than by strategies designed to provide reliable estimates of exposure.

The specific aims of this research were to:

1. Develop and Evaluate an Electronic Direct Postural Assessment System: An electronic postural measurement system was developed to measure shoulder flexion, trunk flexion, lateral bending and torsion and knee flexion. It was intended to provide an accurate determination of body posture categories rather than precise postural angles (as continuous variables). The accuracy of the electronic postural measurement system was evaluated by comparing measurements predicted with the system to measurements obtained with standard postural measurement devices.

2. Assess the Validity of Observational Evaluations of Body Postures in Real Time: The validity of real-time observational characterization of trunk, arm and leg postures was examined by comparing exposure measurements obtained with 2 work-sampling approaches (PATH and a simplified version of PATH) to those recorded with a reference system. The reference consisted of the electronic direct postural measurement system and observation of videotapes. The observations and direct measurements were collected on students performing typical construction tasks in a simulated (training) setting.

3. Develop Guidelines for Reliable and Representative (Unbiased) Samples of Exposure: PATH data collected on 9 ergonomic exposure variables for 10 tasks in 3 highway construction operations were analyzed. The importance of job task as a determinant of exposure was evaluated to assess the efficacy of the task-based assessment strategy. The within- and between- worker components of variance were examined to evaluate the importance of measuring exposures across multiple workers and days. Bootstrapping, a statistical approach that uses computer resampling, was used to investigate the reliability different assessment periods (i.e., number of assessment days) and to provide guidelines for ergonomic exposure assessment in construction work.

B. BACKGROUND AND SIGNIFICANCE

1. Physical Ergonomic Exposures and Musculoskeletal Outcomes

Many types of musculoskeletal disorders are associated with cumulative trauma, a process of accumulating strain on the muscles, tendons, joints and nerves of the body. Such musculoskeletal problems include tension-neck syndrome, rotator cuff tendinitis of the shoulders, herniated spinal discs, carpal tunnel syndrome and epicondylitis for the upper extremities, and Achilles tendonitis, shin splints and knee osteoarthritis for the lower extremities. Strains, sprains and non-specific pain are even more frequently reported outcomes. A comprehensive review of the epidemiologic evidence linking physical ergonomic exposures (i.e., postures, repetitive motions/accelerations and forces) to many types of musculoskeletal disorders of the neck, upper extremity and lower back has been recently published by the National Institute for Occupational Safety and Health (NIOSH) (U.S. Department of Health and Human Services, 1997). Instead, a brief overview of selected epidemiologic reviews and related studies is presented to highlight some of the important physical ergonomic factors of concern to construction workers.

Hagberg (1986) identified studies across a variety of industries that found associations between disorders of the neck/shoulders and work at or above shoulder height, shoulder abduction or flexion > 60 degrees and neck flexion. Kilbolm et al. (1986) reported neck flexion, percentage of work time with the shoulder abducted and frequency of shoulder flexion were also associated with these disorders. Westgaard et al. (1986) found associations among jobs with different levels of static loading on the trapezius (affected by arm postures, among other things) and sick leave due to musculoskeletal illness. More recently, shoulder tendinitis was linked to occupations that require heavy physical work and segmental vibration (Stenlund et al., 1993).

Intensive hand/arm use has been among the most commonly cited work-related factors associated with disorders of the upper extremity (Armstrong, 1993). Exposure to repetitive motions or to forceful exertions of the hands has been linked to tendonitis disorders of the hand and wrist, epicondylitis and carpal tunnel syndrome, among many others (e.g., Kuorinka and Koskinen, 1979; Kurppa et al., 1991; Roto et al., 1984 and Silverstein et al., 1987).

In a review of lower extremity musculoskeletal epidemiology, Jensen and Eenberg (1996) found that knee osteoarthrosis and bursitis were consistently associated with work that required frequent kneeling or squatting postures. At least one study reported that repeated trauma to the knee (e.g., use of a "knee kicker") was associated with bursitis (Thun et al., 1987). An association between time spent standing and musculoskeletal symptoms of the lower extremities has also been reported (Ryan, 1989).

Some work-related factors linked to low-back disorders include heavy physical work (e.g., Riihimaki et al., 1990), non-neutral trunk postures (e.g., Punnett et al., 1991), heavy lifting combined with trunk torsion (e.g., Kelsey et al., 1984), motor-vehicle driving (e.g., Walsh et al., 1989) and trunk motion and acceleration (e.g., Marras et al., 1993). While some studies have demonstrated increasing risk with exposure duration (e.g., Punnett et al., 1991), the complex anatomical characteristics of the back, difficulties in assessing health outcomes related to low-back pain and the multi-causal nature of back injuries have made the exact exposure-response relationship between any specific exposure and back problem very difficult to assess.

In a meta-analysis of the evidence presented in approximately 100 epidemiologic studies on neck and shoulder disorders, loading of the trapezius, inclination of the head and load carrying were identified as potential work-related factors, although no exposure-response relationships could be drawn due, primarily, to a lack of quantitative data on the exposures and potential confounders (Winkel and Westgaard, 1992). In another relatively recent meta-analysis, no clear causal work-related factors were found for neck and shoulder disorders, mainly due to the poor assessment of exposures at these body regions (Stock, 1991).

In a more recent meta-analysis of over 600 epidemiologic studies, NIOSH reported that there was strong evidence for causal relationships between awkward postures and neck/shoulder disorders, a combination of physical ergonomic exposures and upper extremity disorders, and lifting and whole body vibration and back disorders. Furthermore, there was some causal evidence found for many other physical ergonomic exposures. In some cases, exposure-response relationships between physical ergonomic exposures and musculoskeletal disorders were identified (U.S. Department of Health and Human Services, 1997).

In spite of findings such as these, some remain very skeptical on the work-relatedness of cumulative trauma disorders (e.g., Hadler, 1990). This is mainly because of conflicting study results (e.g., differences in the strength of associations) and major flaws in many studies (e.g., lack of control for confounders). Poor characterization of exposure is an important factor behind some of these limitations. Valid and precise measurements of multiple factors (potential exposures and confounders) are needed to help clarify the relationships between work-related exposures and musculoskeletal health outcomes.

2. Why Measure Physical Ergonomic Exposures in Construction?

In 1992 the construction industry had the highest frequency of work-related injuries and illness among all economic sectors, with 13.1 cases per 100 full-time workers (U.S. Department of Labor, 1994a). During this year, there were over 10,000 new cases of nonfatal occupational illness reported in the construction industry, 21% of which were associated with repeated trauma (U.S. Department of Labor, 1994b). In 1993, the incidence rate of injuries due to repeated trauma was 5.4 injuries per 10,000 workers in highway and street construction (U.S. Department of Labor, 1994b).

Epidemiologic studies have demonstrated associations between construction work and musculoskeletal disorders of the back and the upper and lower extremities (e.g., Burkhart et al., 1993; Damlund et al., 1982; Holstrom et al., 1993). However, exposure data for most of these studies are limited to trade or job title, and provide little information about which work-related risk factors contribute most to the excess risk of musculoskeletal problems in this industry.

In spite of the health data and observations that the physical demands of construction work often require awkward postures, heavy lifting and other forceful exertions, little quantitative data exist that describe the magnitude and frequency of these exposures for specific construction job tasks. This is, in part, because construction work generally requires workers to perform multiple tasks with long variable work cycles, making the common cycle-based ergonomic assessment methods and laboratory simulations of job tasks impractical. Additionally, workers having the same job title may have different levels of exposure because the duration and distribution of job tasks for individual workers may vary among workers and from day to day (Winkel and Mathiassen, 1994), an issue of particular relevance for construction work. Alternative exposure assessment methods provide accurate measures of exposure for groups of workers having similar exposure patterns over long time periods (i.e., days) are needed to overcome these obstacles in construction work.

3. COHP and the Use of Work Sampling

Over the past five years, COHP, a project within the Department of Work Environment at the University of Massachusetts Lowell, has been performing research aimed at the prevention of injury and illness among highway construction workers. As part of its ergonomics hazard assessment program, COHP has developed PATH (Posture, Activities, Tools and Handling), an observational work-sampling based technique in which the worker's job tasks, activities, tools used, and weights of material handled, body postures and grasp types are recorded at fixed intervals (Buchholz et al., 1996; Lee, 1993; Lee et al., 1994).

PATH is used to generate frequencies of ergonomic exposures (i.e., percentage of time exposed) to awkward postures, load handling and manual materials handling (MMH), among other things. The frequency of each exposure is estimated as:

$$\text{frequency} = n_e / N \qquad (1.1)$$

where:
frequency = estimated exposure frequency
n_e = # observations with exposure
N= total # of observations

Recording the highway construction operations, job tasks, date and time of data collection, and worker identification codes also allows analysis of the estimated exposure frequency to be stratified by operation, task, day, time and worker.

PATH data may be collected for at least 3 purposes: 1) to identify construction job tasks that present ergonomic hazards, 2) to determine how group exposures for a task are affected by interventions or by different working situations, and 3) to provide exposure data for epidemiologic research. For epidemiologic research, time-weighted exposures can be calculated for individuals, when PATH exposure data are available for the tasks and the frequency with which each task performed is known for each individual.

For highway construction work, PATH data are collected in the context of a hierarchical classification scheme or taxonomy that divides the construction process into stages, operations, trades, and job tasks for each trade (Figure 1). The stages and operations are derived mainly from state highway specifications and contractor production information, and the job tasks performed by each trade during an operation are obtained with worker interviews and the researcher's observations. For other industries where non-routinized work is performed under a different organizational scheme, an analogous taxonomy can be developed to define the job tasks.

Before PATH data collection begins, information is gathered about the construction operation, trades involved with the operation, job tasks and activities performed (i.e., fundamental work elements such as lift, carry and sweep) and tools used. Weights of tools and materials handled by the workers are also recorded before PATH data collection, and are used in the estimates of the loads handled. This information is used to customize the PATH coding template used for data collection (Figure 2).

PATH requires that gross categories of posture be recorded for 3 or 4 regions of the body: trunk, legs, arms and sometimes the neck. The postures were modified from the Ovako Working Postures Analysing System (OWAS) (Karhu et al., 1977; 1981). The PATH trunk-posture categories include: neutral, slight flexion, severe flexion, lateral bending and twisting. Leg postures include: neutral, one leg in air, at least one leg bent 35 degrees, squatting, walking, kneeling, sitting, crawling, and legs not fully supporting the body. Arm posture codes include: neutral, one arm raised at or above shoulder height and both arms raised at or above shoulder height (Figure 3).

COHP has used PATH to characterize the ergonomic exposures of job tasks performed by construction laborers (Paquet et al., 1994), carpenters (Punnett et al., 1996), tilers (Paquet et al., 1995), iron workers (Buchholz and Paquet, 1996; Paquet et al., 1996) and plasterers. Approximately 13,000 observations have been made on close to 100 highway construction workers with a variety of sampling procedures (Table 1).

4. Postural Assessment Methods

A variety methodologies have been developed to assess the postural demands of work. Two types of methods, often used by researchers to quantify the duration and frequency of postural exposures, are direct postural measurement systems and observational methods.

Direct Postural Measurements

Direct measurement of body postures uses markers or measuring devices that are attached directly to the body. The most advanced of these methods include 3-dimensional video-based or diode-based systems, 2-dimensional video-based systems and electrogoniometric systems. With the video-based systems, markers are placed on the body joints of interest and the markers are tracked in 2- or 3-dimensional space with the video cameras and computer equipment. Computer software allows the position of the markers in space to be determined and "links" are drawn between the markers to represent the position of body segments. The 3-dimensional video-based or diode based systems require at least 2 or 3 (and preferably 5) stationary video cameras and are limited to a relatively small observation area, restricting use of these systems to laboratory simulations of job tasks or to static work. Two-dimensional video-based systems only require one camera and can be used more easily in occupational settings. Although the 2-dimensional systems have been found to be reasonably accurate when the photographic plane is perpendicular to the joint of interest, a variety of factors can distort the estimates of joint postures, particularly when multiple joint postures are measured (Paul and Douwes, 1993).

Electrogoniometric systems can also be used in occupational settings and, in some cases, may be more accurate than the 2-dimensional video-based systems (Marras et al., 1992). Electrogoniometric systems used for examining lumbar posture, such as the lumbar motion monitor (LMM) (Chattanooga Group, Inc.) and Penny and Giles electrogoniometers (Penny and Giles Biometrics Limited), have been found to be highly accurate and reliable in laboratory experiments (Marras et al., 1992; Boocock, 1994). The LMM has been used extensively in industrial settings to quantify postural exposures of the lumbar spine (Marras et al., 1993; 1995).

Observational Methods

These methods require an observer to monitor workers visually and record the category of postural exposure either at designated moments or whenever the posture changes. The most rigorous observation methods specify a formal sampling procedure and typically either continuous observation or discrete-interval observation (Genaidy et al., 1994). Continuous observational methods require an observer to note when an exposure category changes, allowing measurement of both the frequency and duration of the exposure category. The assessment can be made in real-time or using video tape. Keyserling (1986) described a continuous simulated real-time method to evaluate trunk and shoulder postures. For this method, computer keyboard keys are assigned to various exposure categories, and the observer presses the appropriate key when an exposure category changes. One body region is coded at a time and computer software is used to determine the frequency and duration of exposure categories for each body region. While continuous observation methods are generally less intrusive than direct postural measurement systems, these methods can be very tiring for jobs having long and irregular cycles, possibly affecting the quality of the data. As an alternative, observations can be made at either fixed-length intervals or randomly selected moments. Assuming that the intervals are short enough and that the observation period is long enough, the proportion of observations in any category will represent the relative frequency of that exposure.

Observational work-sampling techniques, derived from industrial engineering methods, are very useful for estimating the percentage of time that workers perform a particular job activity (Pape, 1992) and have been used for estimating the percentage of time workers are exposed to physical ergonomic hazards (Karhu et al., 1981; Mattila et al., 1993). The assessments are usually made in real-time. With this type of approach the workers' exposures are observed and coded into pre-defined exposure categories at pre-defined instants in time, and the ratio of observations having the exposure to the total number of observations is the estimated percentage of time exposed (see equation 1.1).

Observational work-sampling based approaches have been often used as a postural-assessment tool because it has a number of advantages over other methods of assessment. It can be used in dynamic work settings with little disruption to the work and may be less prone to bias than self reports of exposure. These methods do not require the assumption of regular cycles (length and content) and are useful when information on multiple exposures over long sampling periods is desired.

When the observations are made accurately with PATH or similar methodologies, the precision of the exposure estimates is a function of the probability of exposure and the number of observations used to obtain the exposure estimate:

$$I = 2(\text{alpha}) * [(P * (1-P))/n]^{1/2} \quad (1.2)$$

where:

I = the confidence interval

alpha = z-statistic from a normal probability distribution based on the confidence coefficient

P = the estimate of the proportion of time exposed

n = the number of observations made

note: assumes a normal approximation of the binomial distribution of exposure (from Pape, 1992)

Examples of this relationship are shown in Figure 4. Hundreds of observations are generally required for a precise estimate of exposure frequency, particularly when the probability of exposure approaches 0.5.

5. Validity of Postural Assessment Methods

Validity refers to the absence of bias or systematic measurement error. The validity of an exposure measurement method is represented by the agreement between that method and the actual exposure. The validity of each measure in this study has been examined by comparing it to another measurement system (a reference system) thought to provide an optimal estimate of the actual exposure. Therefore, the term "validity" refers to the inter-method agreement between the measurement system of interest and a reference system. Table 2 summarizes several studies which have assessed this type of validity for postural assessment using direct measurement and observational methods. Direct postural measurement is generally regarded to have the highest accuracy, while the validity of postural assessment using observational techniques is still a topic of debate.

Some of the more favorable evidence regarding the validity of observational techniques has been reported by Keyserling (1986). One seventy-four second cycle of a machine operator's job in an automobile assembly plant was recorded on video tape. The simulated real-time method was used to code trunk-posture and arm-posture categories. The reference method was a video analysis method in which the video-tape was frozen at one-second intervals. For each interval, a mannequin was positioned in a way that imitated the posture on the video. The coordinates of the joints of interest were digitized and entered into the computer, and the postural angles of the trunk and shoulders were calculated. The agreement between the simulated real-time method (Keyserling, 1986) and frame-by-frame analysis was very high for overall estimates of the duration of exposure to trunk and shoulder postures. The duration of exposure to neutral and severely flexed trunk postures was identical and differences for arm-posture categories were less than four seconds (less than 6% of the work cycle). One important limitation of this study was that both methods were subject to similar types of exposure misclassification due to estimating postures in 3 dimensions from a 2-dimensional image on video tape.

Burdorf et al. (1992) assessed the validity of the one of the most widely used observational techniques that utilize discrete-interval observations, OWAS (Karhu et al., 1977; 1981), for characterizing trunk postures during dynamic and sedentary jobs. An electronic inclinometer (a device used to measure the angle relative to gravity) was used as the reference measure. Large differences were found in agreement between the methods for trunk bending greater than 20 degrees among individuals. Agreement was much higher for extreme trunk flexion than moderate trunk flexion, and the recorded exposure frequencies were higher for the observations than for the inclinometer measurements. When each worker's exposure was stratified by less than and greater than 30% work-time spent with the trunk bent, moderate agreement in identifying workers in each of these categories was found between the two methods. When data were stratified by the type of work performed, higher agreement was found for the dynamic work than for the sedentary work.

One important limitation of the study as noted by the researchers, involved the difference in exposure classification definitions between the methods. For the observations, the angle of trunk inclination was defined as the angle between a straight line connecting the pelvis and shoulders and the vertical. The inclinometer was attached directly over the L2-L3 vertebrae and measured only inclination for this region of the back. One possible explanation for the higher frequency of observed moderate trunk postures might be that the shoulders or the thoracic and cervical vertebrae contributed significantly to the trunk inclination during moderate trunk flexion. Lack of precision of the observation method due to the limited number of observations (180) made on each of the 16 workers was also a limiting factor.

De Looze et al. (1994) examined the validity of another postural fixed interval sampling technique, TRAC (described in van der Beek et al., 1992) during a dynamic laboratory-simulated manual materials handling task. The authors used a 2-dimensional diode-based analysis system positioned to minimize distortion, in addition to a video-analysis system, as the reference measure and found that inter-method agreement was high between reference and observational methods for distinguishing kneeling versus standing postures but agreement was low for identifying trunk, arm and other knee postures. The authors found that over half of the disagreements related to trunk posture occurred when the trunk was changing position and they attributed differences to observer error. Disagreement between the methods could have also resulted from slight discrepancies in sampling time between the methods, particularly if postures were changing between categories at the approximate time that each sample was recorded. Definitions of trunk, arm and knee postures may have also been slightly different between the two methods (i.e., markers not aligned consistent with the visual queues used for TRAC).

The validity of PATH for classifying trunk postures has also been investigated (Buchholz et al., 1996). The reference method of measurement was Keyserling's simulated real-time analysis. PATH observations were made on laborers and carpenters who were also recorded on tape for the simulated real-time analysis. The percentage of time that workers were exposed to trunk postures (categorized) was calculated for both methods and moderate differences between the exposure frequencies were found (differences of 4% -24% for the trade specific data and 5%-15% for the pooled data).

This study was limited in several ways. First, the simulated real-time analysis may not have been an appropriate reference measure, as some inaccuracies would be expected when performing a 3-dimensional postural analysis with video tape. During PATH data collection, the observer could change viewing angles for improved classification of postures, while viewing angles on the video tape were limited. Second, the power of the study was limited by small numbers of PATH observations (60 for each trade) and large differences in exposure frequencies could be expected between the methods by chance alone. Assuming that the percentage of time spent in trunk postures was accurately assessed with the simulated real-time method, the 95%-confidence interval of the PATH estimate would be ±12% for the trade-specific data and ± 6% for the pooled data (Pape, 1992). Thus, the actual differences did not exceed what could be predicted by random variability. Given the small number of observations, statistics of agreement (e.g., kappa coefficients) for individual PATH observations and corresponding simulated real-time data might have provided more useful measures of inter-method reliability. Finally, no inter-method assessment of arm, neck and leg postures was made.

6. Exposure Assessment Strategies for Non-Repetitive Work

In epidemiologic research, ideal exposure assessme[illegible] exposure information for each participant in the study over a long period, during which a representative sample of tasks was performed (Burdorf, 1996). Because ideal exposure assessment is not usually feasible due to financial and logistical considerations, strategic methods of exposure assessment are needed for epidemiologic research, as well as for the evaluation of interventions. Unfortunately, research on the optimization of exposure assessment strategies under different conditions is quite limited. Additionally, few studies have examined sampling strategies for characterizing ergonomic exposures in non-repetitive work settings (Winkel and Mathiassen, 1994).

For studies in which average exposure estimates for individuals are desired, the day-to-day variability for each worker should be considered. When there is little day-to-day variability in a worker's exposure, one or a few daily measures may provide a reasonably accurate estimate of that worker's average exposure. As the within-worker variability increases, additional daily measures of exposure are needed to provide a more precise estimate of the worker's average exposure.

An alternative to individual measurements for each worker involves obtaining exposures for a representative sub-sample of an exposure group and applying the group average of exposure to the entire group. With this approach, researchers must place workers into homogenous exposure groups, usually according to their occupations or the job tasks which they perform (Boleij et al., 1995). Each worker's mean exposure is assumed to be similar within the homogenous exposure group. Misclassification of exposure occurs when this is not the case, relative to differences among group means, and the exposure distributions of the different exposure groups overlap. Between-worker variability in exposure among those in a "homogeneous" exposure group can be an important source of misclassification that attenuates the estimation of relative risk (Burdorf, 1993).

In epidemiologic research, by constructing exposure groups that have large differences in average exposure between groups (large between group variance) and have small differences in average exposure within groups (small within group variance), the ability to estimate the strength of association can be optimized (Kromhout and Heederik, 1995). Methods that categorize workers into homogeneous exposure groups rely heavily on the ability to obtain a representative sample of the group's exposure. Therefore, the number of days of assessment for each worker and the number of workers to be studied must be carefully selected.

Obtaining a reliable long-term measure of individual and group exposures requires knowledge about how exposures vary between workers and between days for individual workers. The distribution of ergonomic exposures among workers and over time has been studied only for postural load on the back for relatively few occupations (Burdorf et al., 1994; van der Beek et al., 1995; Burdorf, 1995; Burdorf and van Riel, 1996).

Burdorf et al. (1994) performed a study to examine how exposure to trunk flexion and trunk rotation varied between workers, between days and over the course of a day in a dairy factory. Twenty-eight machine operators were each observed for 30 minutes during the first and second halves of a shift. OWAS observations were made every 20 seconds for a total of 90 observations per sampling period. For each period, the percentage of time each worker spent with the trunk flexed greater than 15 degrees and with the trunk rotated greater than 20 degrees was estimated from the observations. This procedure was repeated 2 months later for each of the workers. The authors found that workers' within-shift exposure variance was greater than both inter-worker and inter-day variance combined. The results of this study demonstrate the importance of measuring non-neutral trunk postures over the entire shift for reliable estimate of this exposure in this industry.

An important limitation of the study was its relatively small number of short sampling periods. For each worker, measurements were made only twice during the shift on two different days. Additionally, while it was thought that differences in the frequency and duration of job tasks contributed to the within-shift variance, no information on job tasks was recorded and therefore could not be considered in the analysis.

Van der Beek et al. (1995) performed a similar study of six occupations to examine the components of variance to non-neutral trunk postures for occupation, worker and observation period within shift, and found similar results. Additionally, exposures were not characterized for each task, and therefore no conclusions could be drawn about the importance of job task on the variance of the exposures.

Burdorf and van Riel (1996) used bootstrapping to help determine the most efficient number of workers to sample in two exposure groups, dairy factory operators and machine operators in a wood-working factory. Their bootstrapping approach first required that exposure data be collected repeatedly on a sample of workers. Sub-samples for a particular number of workers (e.g., 10 workers in a data set having 30 workers) were then selected randomly from the original sample and the average exposure for that sub-sample was calculated. This selection process was repeated 1000 times, and the average and variance of exposure for each particular number of workers was calculated. This process was then repeated for different numbers of workers so that smallest number of workers having a mean and variance similar to the original sample could be identified. With this approach, the authors demonstrated that between 15 and 25 workers were needed to provide a reliable estimate of each occupation's average exposure to trunk flexion when the exposures were recorded for the first half and second half of a shift during two shifts.

7. Significance of this research

Work sampling by observations has advantages over direct exposure measurement because it allows multiple exposures to be assessed simultaneously without interfering with the work. This is a particularly useful research tool for characterizing exposures in construction work, where the dynamic work settings prohibit the extensive use of instrumentation and very little quantitative exposure information exists. However, the validity of observational work-sampling methods for postural assessment is essential for reliance on this approach.

While there has been some advancement in exposure assessment strategies for trunk postures in some occupations, the generalizability of these strategies to other ergonomic exposures (e.g., frequency of awkward arm and knee postures) has not been considered. Additionally, most research has focused on exposure assessment strategies designed to provide reliable average estimates of exposure for occupations and have not examined how ergonomic exposures are influenced by job task.

This research evaluated the validity of observational work sampling for postural assessment and provided information on the appropriate application of work sampling for reliable measures of exposure for construction tasks. The results can be used to improve the selection of ergonomic exposure assessment methodologies for construction and other non-routinized work. In addition, some preliminary information is provided that may aid the evaluation of ergonomic exposures for job tasks and the evaluation of controls and improve exposure characterization efforts in epidemiologic studies.

C. ORGANIZATION OF DISSERTATION

Chapter II describes an evaluation of electronic inclinometers and the lumbar motion monitor (LMM) for the assessment of arm, trunk and knee postures under static experimental conditions. Three sets of measurements were made on 5 subjects with the manual calibration and electronic devices for various postures. Comparisons were made between the manual and electronic measurements. The electronic devices, along with video analysis, provided the reference measurements for the study described in Chapter III.

Chapter III summarizes an evaluation of observational work-sampling for the assessment of body postures during simulated construction work. Five subjects each performed 3 of 6 construction tasks at the New England Laborers' Training Center in Hopkinton, MA. Measurements were made with observational work sampling approaches and the electronic postural measurement system simultaneously, from which comparisons among the methods were made.

Chapter IV describes a study which examines the utility of the task-based approach to exposure assessment and provides guidelines on the appropriate observation time needed for a reliable assessment of exposures. PATH data from 3 construction operations and 10 tasks were evaluated. Analysis of variance (ANOVA) was used to examine the importance of task on average daily exposures for workers and to examine the between-worker and within-worker components of exposure variability within task. Bootstrapping was used to evaluate how the observation time (i.e., days of assessment) affected the reliability of the exposure measurement.

The overall conclusions regarding the validity of work-sampling and its application in the exposure assessment of construction work are presented in Chapter V. Applications in hazard evaluation, evaluation of controls and epidemiologic study are addressed. Areas for future related work are also identified.

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TABLE 1

PATH data collected by the COHP (as of 6/97)

Operation(s)	Trade(s)	Job Tasks	# Wrks.	# Obs.	Sampling Procedure
Laying Pipe, Clean-up, Rip Rap Cons., Catch basins, Demol., Road Widening	Laborers	exposures categorized by operation (not job task)	7	1043	Workers observed for varied amounts of time. No formal randomization procedure used.
Concrete Reinforcement	Iron Workers	ground-level rebar construction, wall-rebar construction, ventilation rebar construction, preparation work, supervising	17	2131	Workers randomly sampled throughout the day over a three week period.
Form Construction	Carpenters	In shop: sawing, building forms, material moving, house keeping, supervising Outdoors: sawing, building forms, material moving, house keeping, supervising, assembling plastic forms, erecting and stripping forms	15	1546	Workers randomly sampled for each location.
	Carpentry Laborers	In shop: mostly housekeeping, material moving Outdoors: mostly form erection, form building	2	305	Randomly sampled with carpenters at each location.
Tunnel Wall Plastering	Plasterers	prepare to apply concrete, first coat, brown coat, miscellaneous	8	~1200	Workers randomly sampled throughout the day over a three week period.
Tunnel Wall Tiling	Tile Mechanics Tile Finishers	mortar mixing and delivery, tile preparation, tiling, wall base preparation, supervision	21	2180	Workers sampled for 15 min (20 obs.), each day for 5 days in random order.
Tunnel Wall Grouting	Tile Finishers	joint preparation, grout preparation, grouting cleaning, miscellaneous	16	1453	Workers randomly sampled throughout the day over a 3-week period.
Jacking Pit Construction	Laborers	top work, pit-wall construction, manual excavation, miscellaneous	10	3219	Workers followed throughout entire shift.

TABLE 2

Summary of studies that have evaluated the validity of direct recording and observational postural assessment methods

Author	Method(s)	Reference Method	Study Population	Results/Conclusions
Boocock et al. (1994)	Flexible electro-goniometer for trunk posture	Fluid filled inclinometer and protractor	Nineteen college students	High agreement between electro-goniometer and reference measurements
Marras et al. (1992)	Lumbar motion monitor 2D video-based analysis system	3D reference frame	N/A LMM positioned while in reference frame	LMM measured low back bending and twisting to within 1 degree of accuracy
Kemmlert (1995)	Observational checklist (PLIBEL)	Observational checklist (AET)	16 postmen or assistants, 2 cashiers, 7 misc. jobs	Relatively high inter-method agreement on items concerning posture
Frannsson-Hall et al. (1995)	Continous observational method (PEO)	Detailed video-analysis	1 cook, 1 furniture mover, 1 secretary, 1 mechanic	High agreement for duration of arm postures, duration and frequency of trunk and neck flexion over-estimated with PEO
Keyserling (1986)	Continuos observational method in simulated real-time (video)	A frame-by-frame video analysis method (measurements made each second) using a computerized manikin	1 machine operator in an automobile assembly plant	High agreement for the duration of time in different trunk and shoulder postures
Burdorf et al. (1992)	Observational work-sampling (OWAS) for trunk postures	Electro-inclinometer	16 workers in dynamic tasks, 14 workers in sedentary tasks	Low agreement between methods for individual workers, higher agreement for dynamic work, moderate agreement between methods when exposure dichotomized
De Looze et al. (1994)	Observational work-sampling (TRAC)	Opto-electronic system to trunk, right arm and arm posture, video analysis to measure left arm and leg posture	3 college students performing a dynamic task in a laboratory	High agreement between methods for kneeling and standing postures, low agreement for trunk, arm and knee postures
Buchholz et al. (1996)	Observational work-sampling (PATH) for trunk postures	simulated real-time video (Keyserling, 1986)	3 laborers 3 carpenter	Poor agreement for group exposure estimates

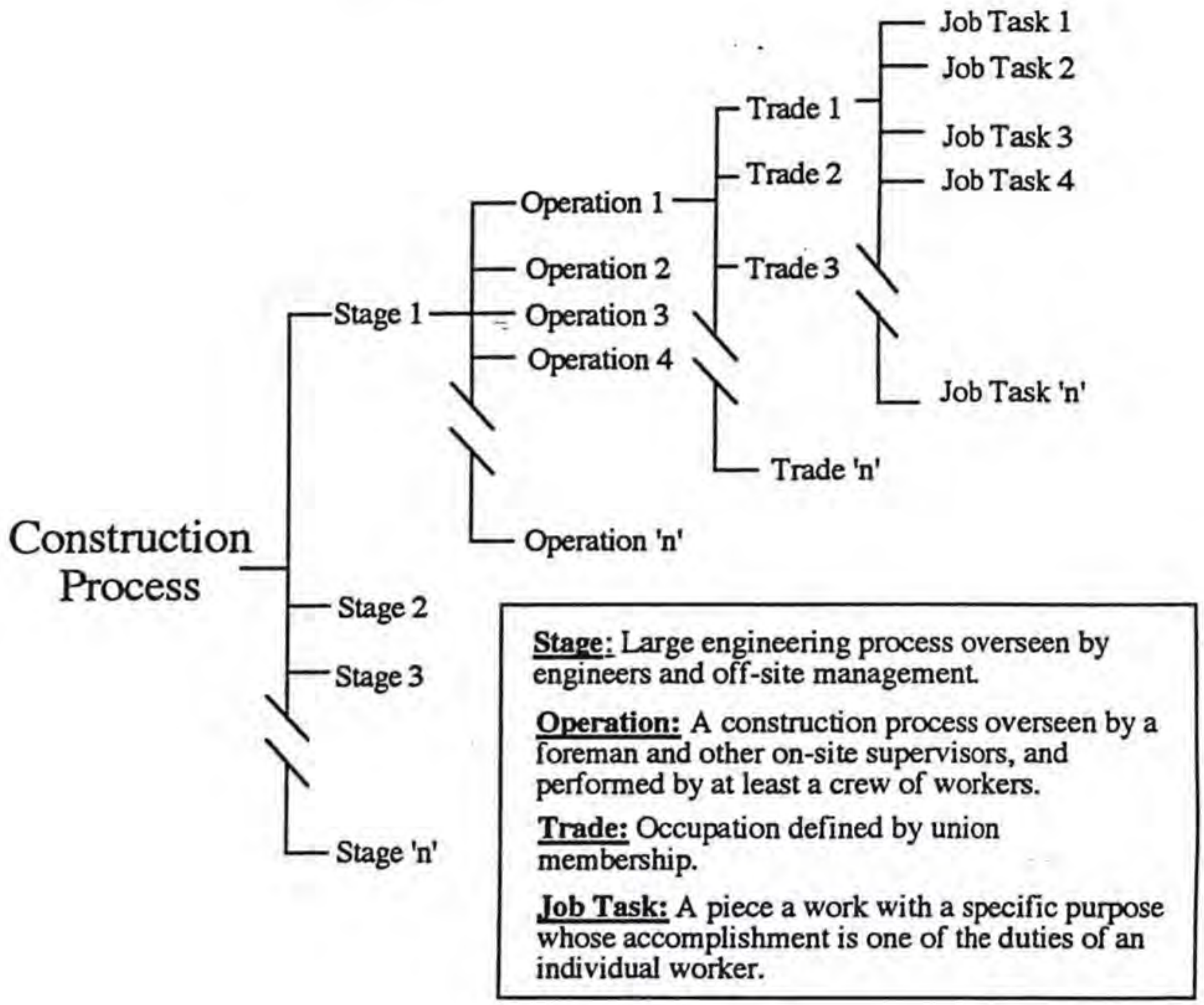

Figure 1. Taxonomy of highway construction work.

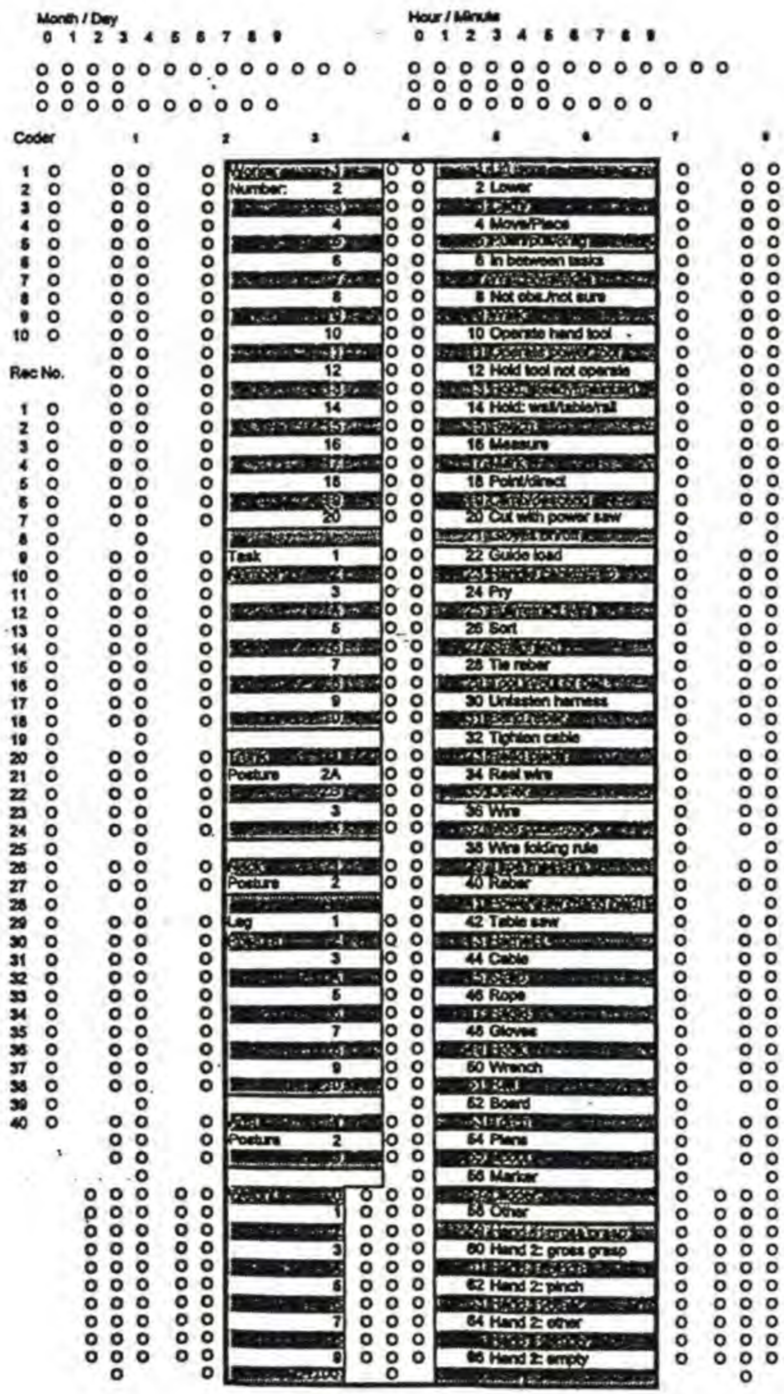

Figure 2. A PATH coding template and scannable data collection sheet that was used to evaluate ergonomic exposures to iron workers during the construction operation of concrete reinforcement. The template is moved across the data collection sheet and identifies the variables to be coded (taken from Buchholz et al., 1996).

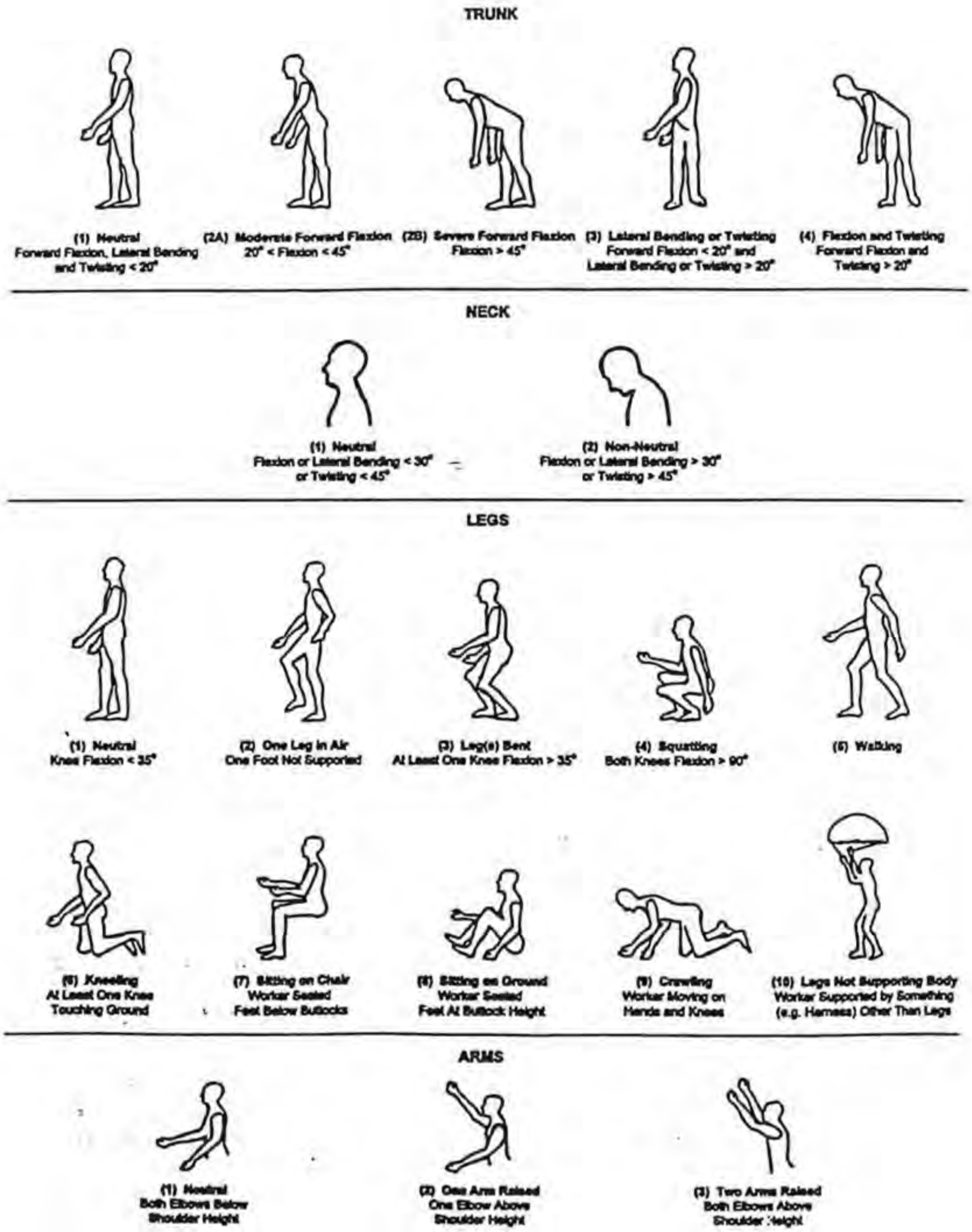

Figure 3. PATH posture codes (taken from Buchholz et al., 1996).

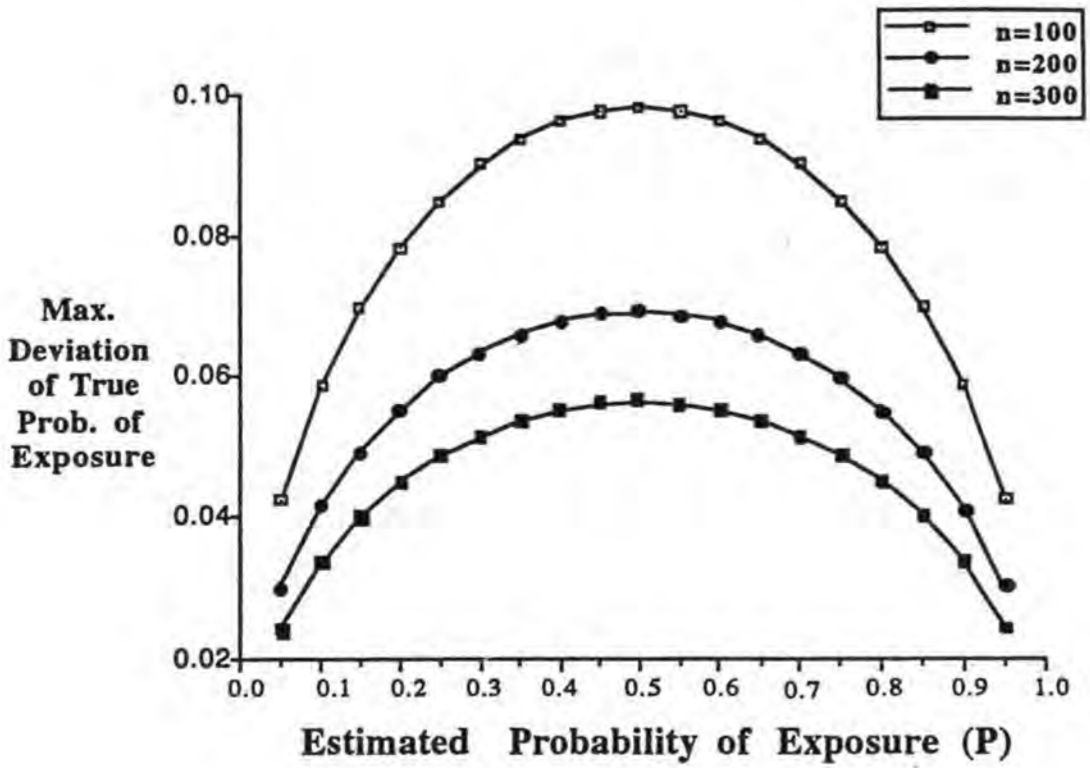

Figure 4. Maximum deviation (l/2 for a 95% confidence coefficient) of the true probability of exposure from the estimated probability of exposure for three different sample sizes calculated with equation 1.2.

CHAPTER II. EVALUATION OF AN ELECTRONIC POSTURAL MEASUREMENT SYSTEM

A. INTRODUCTION

Valid, precise ergonomic exposure assessment methods are desired for epidemiologic research, identification of hazards and evaluation of interventions. In epidemiologic research, exposure-assessment methods that have a systematic measurement bias (lack validity) may either inflate or dilute the association between exposure and health outcome. Even valid methods that lack precision may deflate the association due to non-differential misclassification of exposure. For the evaluation of interventions, reporting bias or low sensitivity (i.e., the inability of an exposure assessment tool to detect small changes in exposure) may inhibit an understanding of an intervention's true effect on exposure.

While awkward postures of the arms, trunk and legs are generally considered to be risk factors for musculoskeletal disorders, the exact relationship between these exposures and risk of musculoskeletal illness still requires clarification. This is partially due to the lack of precise unbiased methods for measuring body posture during work.

The methods that are perhaps most likely to provide precise, unbiased measurements measure posture directly. This can be accomplished by measuring the position of body markers on the body or by measuring devices that are attached directly to the body. Some of the most advanced methods include 2- or 3-dimensional video-based or diode-based systems, electrogoniometric systems and the use of electronic inclinometers. Because 3-dimensional video-based systems usually require a subject to remain in a restricted area and 2-dimensional video systems result in the distortion of the 3-dimensional postural measurements (Paul and Douwes, 1993), electronic goniometers and inclinometers may be best suited for dynamic working conditions.

Electrogoniometric systems are electronic devices that measure the degree of bending across a joint or joints. They employ a variety of transducers that convert mechanical energy into electrical energy. The most common transducers for electrogoniometers are potentiometers that change resistance with varying degrees of joint bending. The change in resistance is converted to a voltage which is used to estimate the amount of joint bending. Electronic inclinometers are another type of electrogoniometer which can also be used to measure the posture of a body segment. The inclinometers are attached to the body areas near or around the joint of interest and provide measurements of a body part's orientation relative to the direction of gravity.

The use of electronic direct-measurement methods for assessing physical ergonomic exposures is becoming increasingly popular. Electrogoniometers and electronic inclinometers have been used in a wide variety of occupation settings to quantify postural loading or movements during work (Weber et al., 1968; Baty et al., 1986; Snijders et al., 1987; Boocock et al., 1994; Marras et al. 1993, 1995; Grant et al., 1995). Additionally, direct-measurement methods have also been used as a means of comparison to evaluate the validity of less sophisticated assessment methods such as observations or self-reported exposure estimates (Burdorf et al., 1992; De Looze et al., 1994; Leskinen et al., 1997).

Few studies, however, have examined the validity of these methods for postural assessment. Marras et al. (1992) tested the accuracy of the LMM (Chattanooga Group, Inc.) for quantifying 3-dimensional posture and motion of the lumbar spine in a laboratory study. The LMM was fixed to a 3-dimensional reference frame, and manipulated along the frame's measurement axes. Measurements recorded with the LMM were within 1 to 2 degrees of those recorded with the 3-dimensional reference frame. While this study demonstrated that the LMM predicted its own orientation quite accurately, no attempt was made to determine how well the LMM predicted actual lumbar position.

Boocock et al. (1994) tested the accuracy of an electrogoniometer (Penny and Giles Biometrics Limited) for measuring lumbar flexion and lateral deviation. Measurements were made on 19 subjects who were required to hold their maximum sagittal and lateral flexion while measurements were made with the electrogoniometer and a reference frame. To calibrate the electrogoniometer, a baseline measurement was made with each subject standing in an upright position. Measurements recorded with the methods were highly correlated and differences averaged within 3 degrees. Buchholz and Wellman (1997) evaluated this electrogoniometer design for the measurement of wrist postures.

The objective of this study was to test the accuracy of the electronic devices for measuring shoulder flexion, knee flexion and trunk postures. It was hypothesized that the accuracy of the electronic inclinometers and LMM would be dependent on the calibration procedure used, with more involved calibration procedures resulting in improved postural measurements. Therefore, the effect of using different calibration conditions on the accuracy of the posture measurements was also evaluated.

B. METHODS

1. Development of a Direct Postural Measurement System

The reference measurement system was designed to provide accurate measurements of trunk, arm and leg postures. The direct postural measurement system consisted of electronic inclinometers to measure upper arm posture, knee flexion, and trunk flexion, coveralls to house the inclinometer wiring, a portable data logger to store the data and LMM to measure trunk side bending and twisting.

The electronic inclinometers (AD05 0-5G, 2.5×10^{-4} g sensitivity, PN#960424, Desktop Laboratories, Inc., 1996) were accelerometers that were sensitive to gravity and produced voltages which varied with their orientation to gravity. While the electronic inclinometer measures acceleration with respect to gravity, the measurement produced in the absence of acceleration is the sensor's position relative to gravity. Therefore, measurements are more accurate under static or isokinetic (constant velocity) conditions than for conditions in which the inclinometers are accelerated.

The electronic inclinometers were powered by a 9-volt battery source and each electronic inclinometer produced approximately 2 to 4 volts, depending on its orientation to gravity. While perpendicular to gravity, each electronic inclinometer produced approximately 3 volts. When tilted forward, the voltage increased and when tilted backward, the voltage decreased.

The inclinometer data were stored in a portable data logger (Onset Computer Corporation, Tattletale Model 5 F, 1995) in a hexadecimal format and downloaded to a portable computer. Two computer programs were written to allow the data logger to store the information produced by the 8 inclinometers. The first allowed data to be collected every 30 seconds for 5 seconds at 10 Hz (i.e., every 30 seconds a new posture is measured during the calibration process). This was to be used during the evaluation and the calibration of the inclinometers. The second allowed data to be collected continuously for up to 20 minutes. Data were collected at 50 Hz for 2 seconds every 30 seconds and at 2 Hz for the remainder of the data collection period.

The data logger was designed to record data from 8 channels and could store up to 480 k bytes of information before being downloaded to a portable computer via a serial cable connector. The hexadecimal file was converted to an ASCII file with a Turbo PASCAL computer program (Borland International, Inc., 1992). This file was then imported into an EXCEL Workbook (EXCEL, version 5.0). The data were then analyzed in EXCEL or imported to a statistical analysis software package for further analysis.

The LMM was selected to measure trunk posture because of its demonstrated validity for measuring lumbar posture (Marras et al., 1992) and utility in the field (Marras et al., 1993; 1995). The LMM is an electrogoniometer that provides measurements of back torsion, as well as forward and lateral bending (Marras et al., 1992). It has been designed to look like an exoskeleton of the spine and to replicate the motion of the lower back. The LMM is strapped on the back of a worker and has sections that are intended to replicate the posterior portions of the lumbar vertebrae. The sections are attached to wires which lead to 3 potentiometers. As the trunk is bent forward or to the side, the sections move about the wires and change the voltage readings of the potentiometers. A fourth potentiometer is used to measure lumbar torsion. The software that accompanies the LMM provides the time at the start of the data collection and the time that each instantaneous sample is collected (Chattanooga Group Inc., 1996).

Electronic measurements of trunk torsion and lateral bending were predicted with the LMM. The LMM produced measurements of lumbar position, velocity and acceleration in three directional planes (flexion, lateral bending and torsion). The measurements made by the LMM were collected at 60 Hz, and were transmitted to a computer with digital telemetry. The LMMI software package (Chattanooga Group, Inc., 1996) allowed the raw data to be stored in ASCII files. The measurements of lumbar lateral bending and torsion were extracted from the ASCII files and used to predict trunk lateral bending and torsion.

2. Location, Subjects and Fitting

The study was conducted in the Occupational Biomechanics Laboratory at the University of Massachusetts Lowell. Five male college students participated in the study. Subjects' age ranged from 19 to 23 years, height ranged from 170 to 187 cm, and weight ranged from 64 to 89 kg. Prior to the study, subjects reviewed and signed an informed consent form (Appendix I). Each subject was fitted with a set coveralls that contained the electronic inclinometer wiring and data logger. The electronic inclinometers and LMM were then secured over the coveralls.

The electronic inclinometers were strapped to each subject. One electronic inclinometer was strapped in line with the lateral portion of each upper arm. Four electronic inclinometers were strapped to the lateral sides of subject's upper and lower legs and positioned horizontally as the subject stood with the legs straight. One electronic inclinometer was attached to the LMM's upper base on the thoracic region of the back (Figure 5). The LMM was secured to the subject's back following recommended fitting procedures (Chattanooga Group, Inc., 1996). The LMM was attached over the subject's lumbar spine with the lower base over L5-S1 and upper base over the thoracic vertebrae. The electronic inclinometer data logger and LMM telemetry transmitter was attached around each subject's waist.

3. Calibration

An adjustable calibration device was designed to allow data obtained with the inclinometers and LMM to be converted to measurements of arm, leg and trunk postural angles. The calibration devices included a weighted inclinometer which was attached to a frame, a protractor which was mounted on the floor of the frame, a hand-held weighted inclinometer and a manual goniometer (Figure 6). For a weighted inclinometer, the weighted end of a pointer is pulled in line with gravity and angles from the pointer equal the deviations from the line of gravity. The weighted inclinometer was aligned with the middle of a person's trunk to measure a trunk flexion and side bending. A person's shoulders, relative to the hips, were aligned with the protractor in the transverse plane to measure trunk torsion. A hand-held weighted inclinometer was aligned with a person's acromion process and lateral epicondyl (bony landmarks of the shoulder and elbow) to measure upper arm posture relative to the shoulder. A manual goniometer was aligned with the lateral mid-sections of the knee and upper and lower legs to measure knee flexion. During the calibration process, the person was required to assume various arm, knee and trunk postures.

Measurements were made with the manual and electronic devices simultaneously to calibrate the direct measurement system. Using these measurements, the voltage outputs of the inclinometers and lumbar measurements of the LMM were used to predict upper arm posture relative to the shoulders, knee flexion, and trunk flexion, lateral bending and torsion.

In order to provide measurements of trunk posture, rather than lumbar posture, the LMM was calibrated similar to the electronic inclinometers. Measurements of lumbar posture were recorded by the LMM while measurements of trunk posture were taken with a weighted inclinometer and protractor. The best fit equations that predicted trunk lateral bending and torsion from lumbar lateral bending and torsion, were then calculated and used in the measurement of trunk posture.

4. Data Collection

Measurements were made with the manual devices and electronic devices simultaneously for 5 types of body postures: right and left shoulder flexion, right and left knee flexion, trunk flexion, trunk lateral bending and trunk torsion. For each type of body posture, measurements were made at 5 or 10 degree intervals throughout the range of motion (5 degree intervals were used at or around the PATH posture category "cut-off" values). Three sets of measurements (3 trials) were made on each subject for each body posture.

Several different calibration conditions (including no calibration for each individual) were evaluated for each body posture (Table 3). When the electronic inclinometers were not calibrated, prediction equations determined in a laboratory study were used to predict the shoulder, trunk and knee flexion from the inclinometer voltages (Appendix II, Figure II-5). These equations were developed in a separate experimental study in which the inclinometers were fixed to a frame and weighted inclinometer, tilted in increments of 10 degrees over a range of 180 degrees with respect to gravity for 5 trials, and allowed the development of equations used to predict tilt relative to gravity from the voltages produced by the inclinometers. When the LMM was not calibrated for individuals, the measurements of lumbar lateral bending and torsion were used as approximations of trunk lateral bending and torsion.

Measurements made during the first trial were used to calibrate the electronic inclinometers and LMM for individual subjects. For each body posture, 2 to 3 additional calibration conditions were evaluated. Each calibration condition involved the use of one or more measurements and the development of a mathematical equation to predict the body posture measurements from the output of the electronic devices. The calibration angles chosen for the study were those thought to facilitate the discrimination between PATH posture categories (e.g., PATH posture category cut-off values were often used) (Buchholz et al., 1996).

For shoulder flexion, the calibrations conditions included: no calibration, 1-point calibration procedure and 14-point calibration procedure. For the 1-point calibration procedure, the subject flexed the shoulders 90 degrees and the voltages produced by the electronic inclinometers were used to adjust the prediction equations in Appendix II, Figure II-5. The difference between the voltages recorded when the subject flexed the shoulders 90 degrees and the voltages obtained when the reference frame was positioned horizontally was added to the subject's recorded voltages on trials 2 and 3. The equations in Appendix II, Figure II-5 were then used to predict the measurements of shoulder flexion from the electronic inclinometer voltages in trials 2 and 3. For the 14-point calibration procedure, measurements were made with the shoulders flexed 0, 10, 20, 30, 40, 50, 60, 70, 80, 85, 95, 105, 115 and 125 degrees. A 3rd-order polynomial equation was used to describe the relationship between the measured values of shoulder flexion and voltages produced by the electronic inclinometers. The equation was then used to predict shoulder flexion from the electronic inclinometer voltages recorded in trials 2 and 3. Equations for each subject are shown in Appendix III, Table III-1.

For knee flexion, the conditions included: no calibration, 1-point calibration procedure, a 2-point calibration procedure and 11-point calibration procedure. For the 1-point calibration procedure, the subject stood with the legs straight and these voltages produced by the electronic inclinometers were used to adjust the prediction equations in

Appendix III in a fashion similar to the 1-point calibration procedure for shoulder flexion. The 2-point calibration procedure required measurements with the knees flexed 20 and 35 degrees. The difference in voltage between the upper and lower inclinometers at both points were used to develop a linear equation which predicted knee flexion from the inclinometer measurements. For the 11-point calibration procedure, measurements were made with the knee flexed 0, 10, 20, 30, 35, 40, 50, 60, 70, 80 and 90 degrees. A 3rd-order polynomial equation was developed with these measurements. The linear and 3rd-order polynomial equations were used to predict knee flexion from the differences in upper and lower inclinometer voltage for trials 2 and 3 (Appendix III, Table III-2).

For trunk flexion, the conditions included: no calibration, 2-point calibration procedure, 3-point calibration procedure and 13-point calibration procedure. The 2-point calibration procedure required measurements at 20 and 45 degrees of trunk flexion. A linear prediction equation was then used to predict trunk postures from voltages in trials 2 and 3. The 3-point calibration procedure required measurements at 0, 20 and 45 degrees of trunk flexion. A 2nd-order polynomial equation was then used to predict trunk postures from voltages in trials 2 and 3. For the 13 point calibration procedure, measurements were made with the trunk flexed 0, 10, 15, 20, 25, 30, 40, 45, 50, 60, 70, 80 and 90 degrees. A 3rd-polynomial equation was used in the prediction of trunk postures in trials 2 and 3 (Appendix III, Table III-3).

For trunk lateral bending, the conditions included: no calibration, 1-point calibration procedure, 3-point calibration procedure and 15-point calibration procedure. The 1-point calibration procedure involved measurements for 20 degrees left and right lateral bending. The 3-point calibration procedure required measurements for 20 degrees of left and right lateral bending, as well as no lateral bending. For the 15 point calibration procedure, measurements were made at 5, 10, 15, 20, 25, 30 and 35 degrees of left and right trunk lateral bending, as well as for no lateral bending. For each of these calibration procedures, linear equations were developed from trial 1 and were used to predict the measurements of trunk lateral bending from measurements of lumbar lateral bending in trials 2 and 3 (Appendix III, Table III-4).

For trunk torsion, the calibration conditions included: no calibration, a 2-point calibration procedure, a 3-point calibration procedure and 7-point calibration procedure. The 2-point calibration required measurements for 20 degrees of right and left trunk torsion, and the 3-point calibration required an additional measurement for 0 degrees trunk torsion. For the 7-point calibration procedure, measurements were made at 0, 10, 20 and 30 degrees of left and right trunk torsion. Simple prediction equations were used for the 2- and 3-point calibration procedures, while a 3rd-order polynomial equation was used for the 7-point calibration procedure (Appendix III, Table III-5). Figure 7 illustrates the data collection for the 3 types of trunk postures.

4. Data Analysis

For each posture type, the prediction equations were applied to the data in all trials when no calibration procedure was used, or in trials 2 and 3 when prediction equations developed from trial 1 were used. The measurements predicted with the electronic devices were compared to those measured with the manual instruments. The predicted body angle measurements of the electronic instrument (either electronic inclinometer or LMM depending on the posture) and the corresponding posture angles measured with a manual instrument were compared with the simple mathematical model:

$$Y = \beta_0 + \beta_1 X \qquad (2.1)$$

where,

Y = predicted body posture (with electronic instruments)

X = measured posture (with manual instruments)

β_0 = intercept

β_1 = slope

The percent of variance in the electronic measurements of postures that was explained by changes in the manual measurements (i.e., coefficient of determination or R^2-statistic) was then computed. This represented the amount of variability in the electronic measurements explained by the actual change in body posture. Remaining variability (i.e., $1-R^2$) represented the error (noise) in the electronic measurements.

Next, the average deviation at each individual body posture measurement was determined as:

$$\text{average deviation} = 1/n \sum_{1}^{n} |\text{difference between the measurements}| \qquad (2.2)$$

where:
n = the number of measurements for each different posture
(15 when there was no calibration, 10 when there was calibration for individuals)

A one-way analysis of variance (ANOVA, F-test) was used to identify statistically significant differences in the error (deviation between those predicted with the electronic device and those obtained with the manual devices) among the calibration methods, and post-hoc Student-Newman-Keuls' multiple range tests were used to identify which calibration conditions were different. For these tests, the calibration procedure was the independent variable and the average deviation from the measurement obtained at each of the body angles with the manual instrument (weighted inclinometer, goniometer or protractor) was the dependent measure. For each posture, the statistical model was represented as:

$$Y_i = \mu + C_i + e_{ij} \tag{2.3}$$

where,

Y_i = predicted mean deviation for calibration procedure i

μ = grand mean deviation

C_i = the effect of calibration procedure i on the mean (5 subjects)

e_{ij} = random error of jth measurement for ith calibration procedure

i = calibration number

j = measurement number for each calibration procedure

The measurements predicted by the electronic instruments with each of the calibration methods and those measured with the manual devices were then stratified into categories of body posture that corresponded with those used in the PATH method (Buchholz et al., 1996). There were 2 categories of shoulder flexion (<90 degrees and ≥ 90 degrees) and knee flexion (<35 degrees and ≥ 35 degrees), 3 categories of trunk flexion (<20 degrees, ≥ 20 and <45 degrees and ≥ 45 degrees) and two categories of trunk lateral bending and torsion (<20 degrees and ≥ 20 degrees).

Agreement between the categories of body posture predicted with the electronic instruments and those measured with the manual devices was calculated in two ways. First, the proportion of agreement was calculated as:

$$P(A) = n/N \tag{2.4}$$

where:

n = # of measurements in which both methods record same category

N = total # of measurements

Second, the kappa coefficient (k), a measure of agreement which corrects for chance agreement between methods, was calculated:

$$k = [P(A) - P(E)] / [1 - P(E)] \qquad (2.5)$$

where:

k = kappa coefficient

P(A) = the proportion of times that the methods agree.

P(E) = the expected proportion of time for chance agreement, based on the probability that a measure will be assigned to each category

note: See Siegel and Castellan (1988) for the computation of P(A) and P(E) needed for K.

C. RESULTS

1. Shoulder Flexion

Shoulder flexion measured with the weighted inclinometer explained much of the variance in the shoulder flexion predicted with the electronic inclinometers for all calibration procedures ($R^2 \geq 0.93$). Generally, the greatest errors observed were for shoulder flexion < 40 degrees or > 115 degrees (Figure 8).

For left shoulder flexion, the average deviation between measurements made with the weighted inclinometer and those predicted by the electronic inclinometers was < 6 degrees for all calibration conditions for 50 to 90 degrees of shoulder flexion (Figure 9). When no calibration or the 1-point calibration procedure was used, the average deviation of the measurements from those made with the weighted inclinometer was < 6 degrees at 95 and 105 degrees. For shoulder flexion < 20 degrees or > 115 degrees, the calibration procedure closely predicted left shoulder flexion measured with the weighted inclinometer, but was least accurate at 95 and 105 degrees of shoulder flexion. Differences in average deviation between the measurements predicted with the electronic inclinometers and those measured with a weighted inclinometer were not statistically significant among the calibration methods ($F_{2,42} = 0.97$, Pr>F=0.39).

For right shoulder flexion, the average deviation fluctuated between 5 and 8 degrees for right shoulder flexion ranging between 50 and 105 degrees (Figure 10). The 14-point calibration procedure was the most accurate for right shoulder flexion < 20 degrees but was least accurate for right shoulder flexion of 105 degrees. Differences between measurements predicted with the electronic inclinometers and measured with a weighted inclinometer were statistically significant among the calibration methods ($F_{2,42} = 3.75$, Pr>F=0.03), with the average deviation of the 1-point calibration significantly different than the 13-point calibration procedure ($p<0.05$, Student-Newman-Keul's multiple range test).

When measurements were divided into 2 categories of shoulder flexion (< 90 degrees, and ≥ 90 degrees), agreement between measurements made with the weighted inclinometer and those predicted by the electronic inclinometers was extremely high for all 3 calibration conditions (Table 4). For the left shoulder, agreement was high for flexion ≤ to 85 degrees or ≥ 95 degrees, but was low for 90 degrees of flexion (Table 5). Similar results were found for right shoulder flexion, with the exception of high agreement at 90 degrees of shoulder flexion when no individual calibration procedure was used (Table 6).

2. Knee Flexion

Knee flexion measured with the goniometer explained much of the variance in knee flexion predicted with the electronic inclinometers when measurements were calibrated for individual subjects ($R^2 > 0.81$). The most variance was explained with the goniometer measurements for the 1-point calibration procedure. When no individual calibration procedure was used, the amount of variance in the predicted measurements explained by the goniometer measurements was smaller ($R^2<0.71$) (Figure 11).

The average deviation of measurements for left and right knee flexion, made with the goniometer, differed significantly among the calibration conditions (Left Knee: $F_{3,40} = 5.78$, Pr>F=0.0002; Right Knee: $F_{3,40} = 20.46$, Pr>F=0.0001), with the mean deviation for measurements made without individual calibration significantly different from those of the remaining calibration conditions ($p<0.05$, Student-Newman-Keuls' multiple range test). For left knee flexion, overall mean deviation from measurements made with the goniometer was 13.7 degrees with no individual calibration and ranged between 7.9 and 8.9 degrees for the remaining calibration conditions. The 1-point calibration procedure resulted in the smallest deviation from the goniometer measurements for left knee flexion exceeding 50 degrees (Figure 12). For right knee flexion, overall average deviation from measurements made with the goniometer was 16.5 degrees when the inclinometers were not calibrated for the individual and ranged between 8.1 and 8.8 degrees for the remaining conditions. The observed deviations from the goniometer measurements were lowest when the 1-point calibration procedure was used (Figure 13).

When the measurements were divided into 2 categories of knee flexion (<35 degrees, and ≥ 35 degrees), agreement between the measurements obtained with the goniometer and electronic inclinometers was high for all calibration conditions (Table 7). For the left knee, agreement between the measurement ≥ 35 degrees flexion was highest for the 2- and 11-point calibration procedures (Table 8). For the right knee, agreement between the conditions at or near 35 degrees flexion was highest when the 1-point calibration procedure was used (Table 9).

3. Trunk Flexion

Trunk flexion measured with a weighted inclinometer explained much of the variance in trunk flexion predicted with the electronic inclinometer (R^2>0.86) (Figure 14). The amount of variance explained by the weighted inclinometer measurements was almost identical for the no, 3-point and 13-point calibration conditions, but was smaller for the 2-point calibration condition. For the conditions that required individual calibration, the largest errors in the electronic inclinometer's measurements occurred during extreme flexion. Under the no-calibration condition, the largest errors in the electronic-inclinometer measurements were from 40 to 60 degrees of trunk flexion (Figure 15).

Overall, the average deviation ranging between trunk flexion predicted with the electronic inclinometer and measured with the weighted inclinometer was 5.6 to 8.7 degrees (Figure 15). Deviation from trunk flexion measured with the weighted inclinometer was, for most of the calibration conditions, within 6 degrees, except when the trunk was flexed 90 degrees. No significant differences ($F_{3,48} = 1.23$, Pr>F=0.31) in deviation from the weighted inclinometer measurements were found among the calibration methods.

When the measurements were divided into 3 categories of trunk flexion (< 20 degrees, ≥ 20 degrees and < 45 degrees, and ≥ 45 degrees), agreement between measurements obtained with the weighted inclinometer was high for all calibration conditions (Table 10). Agreement was similar among the different calibration conditions for different degrees of trunk flexion measured with the weighted inclinometer (Table 11).

4. Trunk Lateral Bending

The amount of variability in the LMM measurements of trunk lateral bending explained by the weighted-inclinometer measurements of trunk lateral bending was extremely high for all calibration conditions (R^2>0.97) (Figure 16). However, average deviation from measurements obtained with the weighted inclinometer differed significantly among the calibration conditions ($F_{3,56}$ = 12.09, Pr>F=0.0001), with the no-calibration condition significantly different than the remaining calibration conditions (p<0.05, Student-Newman-Keuls' multiple range test). Overall mean deviation from the weighted inclinometer was 4.9 degrees when the LMM was not calibrated for each individual and ranged between 1.9 and 2.6 degrees for the remaining calibration conditions. Average deviation from trunk lateral bending measured with a weighted inclinometer was $\leq$ 4 degrees for the entire range of measurements when the LMM was calibrated for each individual (Figure 17).

When measurements of trunk lateral bending were divided into 2 categories (< 20 degrees, and $\geq$ 20 degrees), agreement between measurements made with the weighted inclinometer and LMM was high, particularly when the LMM was calibrated for each individual (Table 12). The agreement between the conditions at or near 20 degrees of trunk lateral bending was also higher when the LMM was calibrated for each individual (Table 13).

5. Trunk Twisting

The amount of variability in the LMM measurements of trunk torsion explained by the protractor measurements of trunk torsion was high for all calibration conditions, being lowest for the 7-point calibration procedure (R^2>0.91) (Figure 18). Overall average deviation from the protractor measurements ranged from 3.2 to 4.5 degrees, and was generally within 6 degrees across the entire range of measurements for all calibration conditions (Figure 19). There were no significant differences ($F_{3,24}$ = 1.17, Pr>F=0.34) in the average deviation from the measurements made with the protractor among the different calibration conditions.

When the measurements were divided into 2 categories of trunk torsion (<20 degrees, and ≥ 20 degrees), agreement between the protractor measurements and LMM measurements was highest when the 1-point calibration procedure was used (Table 14). Agreement at or near 20 degrees of trunk torsion was similar among calibration conditions over the range of measurements (Table 15).

D. DISCUSSION

1. Accuracy of the Electronic Postural Assessment System

The electronic inclinometers produced estimates of shoulder flexion similar to measurements made with the weighted inclinometer for all calibration conditions, particularly for shoulder flexion ranging between 50 and 90 degrees. Calibrating the electronic inclinometers for each individual did not appear to greatly increase accuracy of the measurements. Using a 14-point calibration procedure to calculate a 3rd-order polynomial prediction equation improved measurements for only mild shoulder flexion (<20 degrees) and extreme left shoulder flexion (> 105 degrees) and did not enhance the agreement for measuring broad categories of shoulder flexion (< 90 and ≥ 90 degrees).

The electronic measurements closely approximated those made with the weighted inclinometer for trunk flexion < 70 degrees, with high agreement between the measurement methods when measurements were grouped into 3 categories of trunk posture. Measurements of trunk flexion made with the electronic inclinometers were not improved when the calibration was performed on individuals.

The fact that the more complex calibration procedures did not improve the accuracy of the electronic measurements of shoulder and trunk flexion in this study may be because of the relationship between the voltages produced by the electronic inclinometers and their position relative to gravity. While this relationship is best described with a 3rd-order polynomial equation (Appendix II, Figure II-4) over a range of 180 degrees, the relationship over a range of 140 degrees ($\pm$ 70 degrees from the horizontal) is more linear. This range is more representative of the body postures actually measured in this study. Therefore, the accuracy of the inclinometers may not have been significantly improved with the calibration procedures for the range of shoulder and trunk flexion studied here.

Average differences between the measurements obtained with the goniometer and electronic inclinometers were between 8 to 10 degrees for knee flexion up to 90 degrees. Measurements of knee flexion required the orientation of both the upper and lower portions of the leg to be determined. The difference between the measurements made with the electronic inclinometers located above and below the knee was used to predict knee flexion. The increased error observed in the electronic measurements may have been due to the use of 2 inclinometers rather than 1 inclinometer to predict posture. Unlike the measurements of shoulder and trunk flexion, calibration of the electronic inclinometers for individuals improved the accuracy of the measurements. However, there was little difference in accuracy among the individual calibration methods.

Measurements of lumbar posture made with the LMM to predict trunk posture were very similar to those made with the weighted inclinometer when the LMM was calibrated for each individual for measurements of lateral bending and for all calibration conditions (including no calibration) for measurements of trunk torsion. Although the LMM has been designed specifically to measure lumbar posture, the results of this evaluation suggest that the LMM can also be used to estimate trunk posture.

2. Limitations

This evaluation was conducted in a controlled laboratory setting and measurements were made on static postures. Measurements made with the electronic system probably are more representative of ideal conditions for postural assessment, rather than those typically observed on work sites. The electronic inclinometers are sensitive to acceleration and therefore measurement error may increase when the body region of interest is accelerated or decelerated. The LMM uses potentiometers and measurements of posture are not as sensitive to movement.

Measurements made with the weighted inclinometer, goniometer and protractor were used as references for this evaluation. The accuracy of the reference measurements were dependent on the researcher's ability to align the instrument with the subject's body and the precision of the instrument. The lack of a true reference system could affect the results of the evaluation of the electronic postural measurement system. Results of a pilot study demonstrated that the measurements obtained with these instruments closely resembled measurements recorded with a highly sophisticated diode-based video analysis system (differences were usually < 2 degrees), with the greatest discrepancies observed in knee flexion (with observed differences of up to 8 degrees) (Appendix II). While the manual instruments appear to measure shoulder and arm postures accurately, the measurement of knee flexion with the goniometer may not be an ideal reference. This is may be because the measurement of knee flexion involve 2 (upper and lower legs) rather than 1 electronic inclinometer and therefore the possible increase the overall measurement error.

Two statistical methods were used to evaluate the agreement between the manual and electronic methods for characterizing categories of body posture. The proportion of agreement between methods ignores the role of chance agreement in the analysis, while the kappa coefficient is a measure of agreement that accounts for the role of chance. Therefore, when chance agreement is high between methods, the proportion of time that the methods agree may be high and the kappa coefficient may be low, limiting the conclusions that can be made from the results. This problem was avoided in this study because the frequency of postures in each category was controlled to help minimize the role of chance agreement.

The measurements of knee flexion produced by the electronic inclinometers do not allow leg postures such as standing, kneeling, squatting or walking to be distinguished from one another. Additionally, measurements of knee flexion during walking may not be accurate due to excessive acceleration of the instruments. An additional postural assessment method, such as simulated real-time observation (Keyserling, 1986), is needed to identify the types of leg postures used.

E. CONCLUSIONS

The electronic direct postural assessment system evaluated in this study provided accurate measures of body postures with no or very simple calibration procedures. The system appeared to be least accurate in the measurement of knee flexion. However, agreement between the manual and electronic assessment methods was high for measurement categories of posture, including categories of knee flexion. This system should be used with an additional method such as real-time observations or video analysis to measure knee flexion for standing, kneeling or squatting leg postures. The electronic postural assessment system should provide useful measures of body posture during static or semi-static working conditions, particularly when categories of posture are desired.

F. RECOMMENDATIONS

1. For measuring shoulder, knee and trunk postures on a continuous scale with the electronic inclinometers and LMM, the recommended calibration procedures are:

   Shoulder Flexion: no individual calibration for shoulder flexion >30 deg., 13-point calibration for shoulder flexion <30 degrees but not for shoulder flexion ~105 deg

   Knee Flexion: 1-point calibration (knees neutral)

   Trunk Flexion: no individual calibration unless trunk flexion of 45-70 degrees is of greatest interest, 3-point calibration for trunk flexion of 45-70 degrees

   Trunk Lateral Bending: 3-point calibration (20 degrees left, 0 degrees, 20 degrees right)

   Trunk Torsion: 2-point calibration (20 degrees left, 20 degrees right)

2. For measuring shoulder, knee and trunk postures in broad categories that correspond to the PATH posture categories, the recommended calibration procedures are:

   Shoulder Flexion: no individual calibration

   Knee Flexion: 2-point calibration (20 degrees, 35 degrees flexion)

   Trunk Flexion: no individual calibration

   Trunk Lateral Bending: 3-point calibration (20 degrees left, 0 degrees, 20 degrees right)

   Trunk Torsion: 2-point calibration (20 degrees left, 20 degrees right)

3. Measurements were made only on static postures. The use of the electronic-inclinometers under dynamic conditions (e.g., intensive arm use, rapid changes in trunk flexion or during walking activities) will most likely decrease the accuracy of the measurements.

The use of the electronic inclinometers for work situations that are dynamic is not recommended without first evaluated them under such circumstances.

4. The analyses in this study provided information on the accuracy of the electronic inclinometers and LMM for a group of 5 subjects. Additional statistical tests should be performed to examine the effect of subject on the accuracy of the calibration conditions. If the effect of subject is small for a calibration procedure, then calibrating for individuals in the future may not be necessary (i.e., the equations in Appendix III could be used). Calibration for individual subjects will be necessary in the future if the prediction equations differ greatly among subjects and, until such additional analyses are completed, it is recommended that calibration for individual subjects be performed using the calibration procedures mentioned above for knee flexion, trunk lateral bending and trunk torsion.

5. When exposure measurements on lumbar lateral bending, torsion and flexion are desired, the calibration equations and procedures described in this chapter do not apply. For these exposures, the measurements recorded by the LMM should be used.

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TABLE 3

Summary of the calibration conditions for the postural measurements made with the electronic inclinometers and LMM

Electronic Inclinometers

Shoulder Flexion

- None, 3rd-order polynomial prediction equation
- 1-Point (at 90 deg. shoulder flexion), 3rd-order polynomial prediction equation
- 14-Point (in 5 or 10 degree intervals from 0 to 125 deg. shoulder flexion), 3rd-order polynomial prediction equation

Knee Flexion

- None, 3rd order polynomial prediction equation
- 1-Point (at 0 deg. knee flexion), 3rd-order polynomial prediction equation
- 2-Point (at 20 and 35 deg. knee flexion), simple prediction equation
- 11 Point (in 5 or 10 degree intervals from 0 to 90 deg. knee flexion), 3rd order polynomial prediction equation

Trunk Flexion

- None, 3rd-order polynomial prediction equation
- 2-Point (20 and 45 deg. trunk flexion), simple prediction equation
- 3-Point (0, 20 and 45 deg. trunk flexion), 2nd-order polynomial prediction equation
- 13-Point (in 5 or 10 deg. intervals from 0 to 90 deg. trunk flexion), 3rd-order polynomial prediction equation

LMM

Trunk Lateral Bending

- None, LMM measurement
- 2-Point (at 20 deg. right and left lateral bending), simple prediction equation
- 3-Point (at 0 and 20 deg. right and left lateral bending), simple prediction equation
- 15-Point (in 5 deg. intervals from 35 deg. right to 35 deg. left lateral bending), simple prediction equation

Trunk Torsion

- None, LMM measurement
- 2-Point (20 deg. right and left torsion), simple prediction equation
- 3-Point (0 and 20 deg. right and left torsion), simple prediction equation
- 7-Point (in 10 deg. intervals from 30 deg right and left torsion), simple prediction equation

TABLE 4

Inter-method reliability (proportion of agreement and kappa coefficient) between measurements made with a weighted inclinometer (WI) and electronic inclinometers (EI) for 2 categories of shoulder flexion (<90 degrees, and ≥90 degrees) for 5 subjects

	Left Shoulder Flexion		Right Shoulder Flexion	
Methods	Agreement	Kappa	Agreement	Kappa
WI and EI (no calibration)	0.95	0.89	0.95	0.88
WI and EI (1-point calibration)	0.96	0.90	0.93	0.84
WI and EI (14-point calibration)	0.96	0.90	0.92	0.80

TABLE 5

Proportion of time that electronic inclinometer measurements correctly predicted categories of left shoulder flexion (< 90 degrees, and > 90 degrees) measured with a manual inclinometer (5 subjects, 3 trials for no calibration, 2 trials for remaining procedures)

Shoulder Flexion: Electro-Inclinometer	Shoulder Flexion: Manual Inclinometer Measurements (deg.)														
	0	10	20	30	40	50	60	70	80	85	90	95	105	115	125
No Calibration	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9	0.5	1.0	1.0	1.0	1.0
1-Point Calib.	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9	0.4	0.9	1.0	1.0	1.0
14-Point Calib.	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.6	1.0	1.0	1.0	1.0

TABLE 6

Proportion of time that electronic inclinometer measurements correctly predicted categories of right shoulder flexion (<90 degrees, and > 90 degrees) measured with a manual inclinometer (5 subjects, 3 trials for no calibration, 2 trials for remaining procedures)

Shoulder Flexion:	Shoulder Flexion: Manual Inclinometer Measurements (deg.)														
Electro-Inclinometer	0	10	20	30	40	50	60	70	80	85	90	95	105	115	125
No Calibration	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.8	0.7	0.9	1.0	1.0	1.0	1.0
1-Point Calib.	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.2	0.7	1.0	1.0	1.0
14-Point Calib.	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.4	0.7	1.0	1.0	1.0

TABLE 7

Inter-method reliability (proportion of agreement and kappa coefficient) between measurements made with a manual goniometer (MG) and electronic inclinometers for 2 categories of knee flexion (<35 degrees, and ≥35 degrees) for 5 subjects

	Left Knee Flexion		Right Knee Flexion	
Methods	Agreement	Kappa	Agreement	Kappa
MG and EI (no calibration)	0.82	0.64	0.77	0.54
MG and EI (1-point calibration)	0.88	0.75	0.84	0.68
MG and EI (2-point calibration)	0.87	0.72	0.87	0.72
MG and EI (11-point calibration)	0.87	0.72	0.89	0.76

TABLE 8

Proportion of time that electronic inclinometer measurements correctly predicted categories of left knee flexion (< 35 deg., and > 35 deg.) measured with a goniometer (5 subjects, 3 trials for no calibration, 2 trials for remaining procedures)

Knee Flexion: Electro-Inclinometer	Knee Flexion: Manual Goniometer Measurements (deg.)										
	0	10	20	30	35	40	50	60	70	80	90
No Calibration	1.0	1.0	1.0	0.7	0.5	0.5	0.7	09	0.9	0.9	1.0
1-Point Calib.	1.0	1.0	1.0	1.0	0.3	0.4	0.8	0.9	1.0	1.0	1.0
2-Point Calib	1.0	1.0	1.0	0.6	0.7	0.9	0.9	0.9	1.0	1.0	1.0
11-Point Calib.	1.0	1.0	0.9	0.4	0.7	0.9	0.9	0.9	1.0	1.0	1.0

TABLE 9

Proportion of time that electronic inclinometer measurements correctly predicted categories of right knee flexion (< 35 deg., and > 35 deg.) measured with a goniometer (5 subjects, 3 trials for no calibration, 2 trials for remaining procedures)

Knee Flexion: Electro-Inclinometer	Knee Flexion: Manual Goniometer Measurements (deg.)										
	0	10	20	30	35	40	50	60	70	80	90
No Calibration	1.0	1.0	1.0	0.6	0.4	0.5	0.5	0.7	0.8	0.9	1.0
1-Point Calib.	1.0	1.0	1.0	1.0	0.5	0.5	0.8	1.0	1.0	1.0	1.0
2-Point Calib	1.0	1.0	1.0	0.67	0.8	0.9	0.9	0.9	1.0	1.0	1.0
11-Point Calib.	1.0	1.0	1.0	0.4	0.7	0.9	0.9	0.9	1.0	1.0	1.0

TABLE 10

Inter-method reliability (proportion of agreement and kappa coefficient) between measurements made with a weighted inclinometer and electronic inclinometers for 3 categories of trunk flexion (<20 degrees, 20≤ and < 45 degrees, and ≥45 degrees) for 5 subjects

Methods	Agreement	Kappa
WI and EI (no calibration)	0.88	0.82
WI and EI (2-point calibration)	0.87	0.79
WI and EI (3-point calibration)	0.87	0.79
WI and EI (13-point calibration)	0.88	0.82

TABLE 11

Proportion of time that electronic inclinometer measurements correctly predicted the PATH trunk flexion categories (< 20, > 20 and <45, and > 45) measured with a manual inclinometer (5 subjects, 3 trials for no calibration, 2 trials for remaining procedures)

Trunk Flexion: Electro-Inclinometer	Trunk Flexion: Manual Inclinometer Measurements (deg.) 0	10	15	20	25	30	40	45	50	60	70	80	90
No Calibration	1.0	1.0	0.9	0.5	0.9	1.0	0.7	0.6	0.9	1.0	1.0	1.0	1.0
2-Point Calib.	1.0	1.0	0.9	0.5	0.7	0.9	0.8	0.7	1.0	1.0	1.0	1.0	1.0
3-Point Calib.	1.0	1.0	0.8	0.5	0.9	0.9	0.9	0.6	0.9	1.0	1.0	1.0	1.0
13-Point Calib.	1.0	1.0	0.9	0.6	0.9	0.9	0.9	0.6	0.9	1.0	1.0	1.0	1.0

TABLE 12

Inter-method reliability (proportion of agreement and kappa coefficient) between measurements made with a weighted inclinometer and LMM for 2 categories of trunk lateral bending(<20 degrees, and > 20 degrees)

Methods	Agreement	Kappa
WI and LMM (no calibration)	0.80	0.59
WI and LMM (2-point calibration)	0.91	0.82
WI and LMM (3-point calibration)	0.92	0.84
WI and LMM (15-point calibration)	0.92	0.84

TABLE 13

Proportion of time that LMM measurements correctly predicted the PATH trunk lateral bending categories (<20 deg., and > 20 deg.) measured with a manual inclinometer (5 subjects, 3 trials for no calibration, 2 trials for remaining procedures)

Trunk Side Bending: LMM	Trunk Side Bending: Manual Inclinometer Measurements (deg.) 35 L	30 L	25 L	20 L	15 L	10 L	5 L	0	5 R	10 R	15 R	20 R	25 R	30 R	35 R
No Calibration	1.0	0.6	0.1	0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.1	0.8	1.0	1.0
2-Point Calib.	1.0	1.0	0.8	0.3	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.3	1.0	1.0	1.0
3-Point Calib.	1.0	1.0	0.9	0.5	1.0	1.0	1.0	1.0	1.0	1.0	0.9	0.4	1.0	1.0	1.0
15-Point Calib.	1.0	1.0	0.9	0.4	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.4	1.0	1.0	1.0

note: L = Left, R = Right

TABLE 14

Inter-method reliability (proportion of agreement and kappa coefficient) between measurements made with a weighted inclinometer and LMM for 2 categories of trunk torsion (< 20 degrees, and > 20 degrees)

Methods	Agreement	Kappa
Prot. and LMM (no calibration)	0.82	0.63
Prot. and LMM (1-point calibration)	0.89	0.79
Prot. and LMM (3-point calibration)	0.86	0.70
Prot. and LMM (7-point calibration)	0.83	0.65

TABLE 15

Proportion of time that LMM measurements correctly predicted the PATH trunk torsion categories (< 20 deg., and > 20 deg.) measured with a protractor (5 subjects, 3 trials for no calibration, 2 trials for remaining procedures)

Trunk Twisting: LMM	Trunk Twisting: Protractor Measurements (deg.) 30 L	20 L	10 L	0	10 R	20 R	30 R
No Calibration	1.0	0.67	1.0	1.0	0.93	0.47	0.93
2-Point Calib.	1.0	0.33	1.0	1.0	1.0	0.33	1.0
3-Point Calib.	0.93	0.53	1.0	1.0	1.0	0.40	1.0
7-Point Calib.	0.93	0.47	1.0	1.0	1.0	0.47	0.93

note: L = Left, R = Right

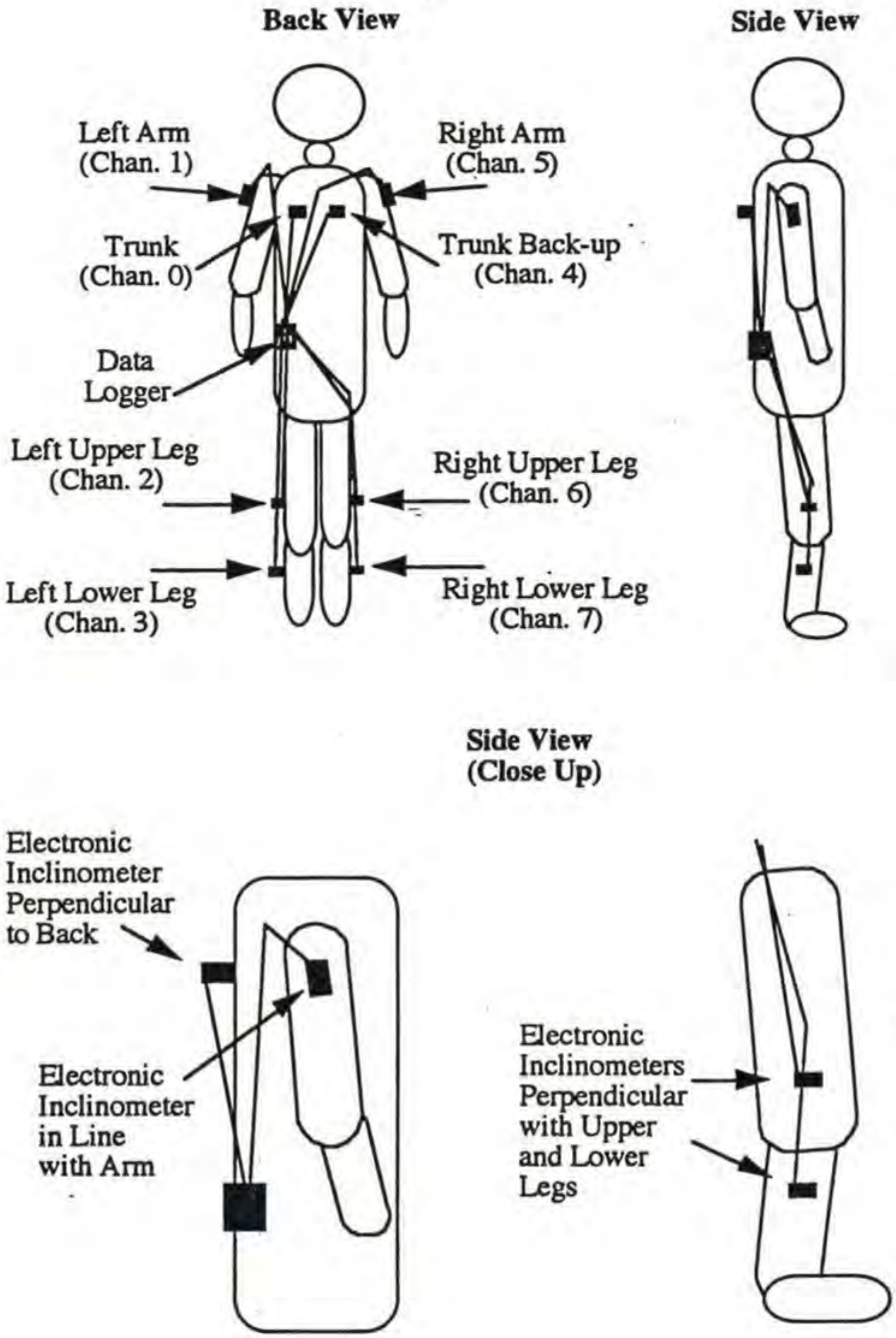

Figure 5. Schematic illustrating the location of the electronic inclinometers on the study subjects.

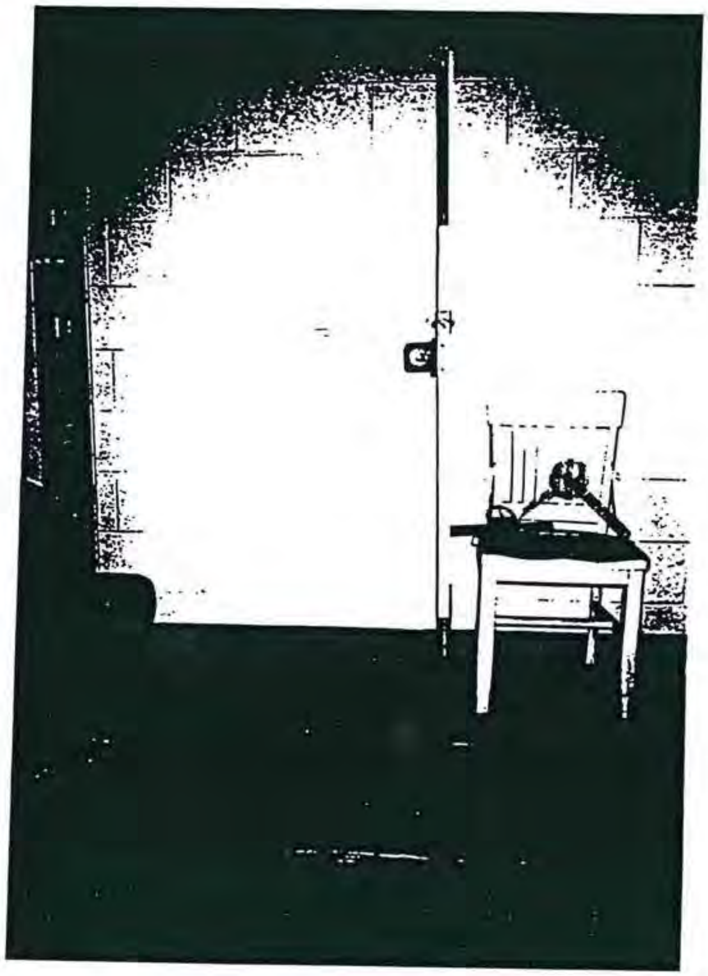

Figure 6. The calibration instruments: a weighted inclinometer attached to a frame, protractor on the floor of the frame, hand-held weighted inclinometer and goniometer.

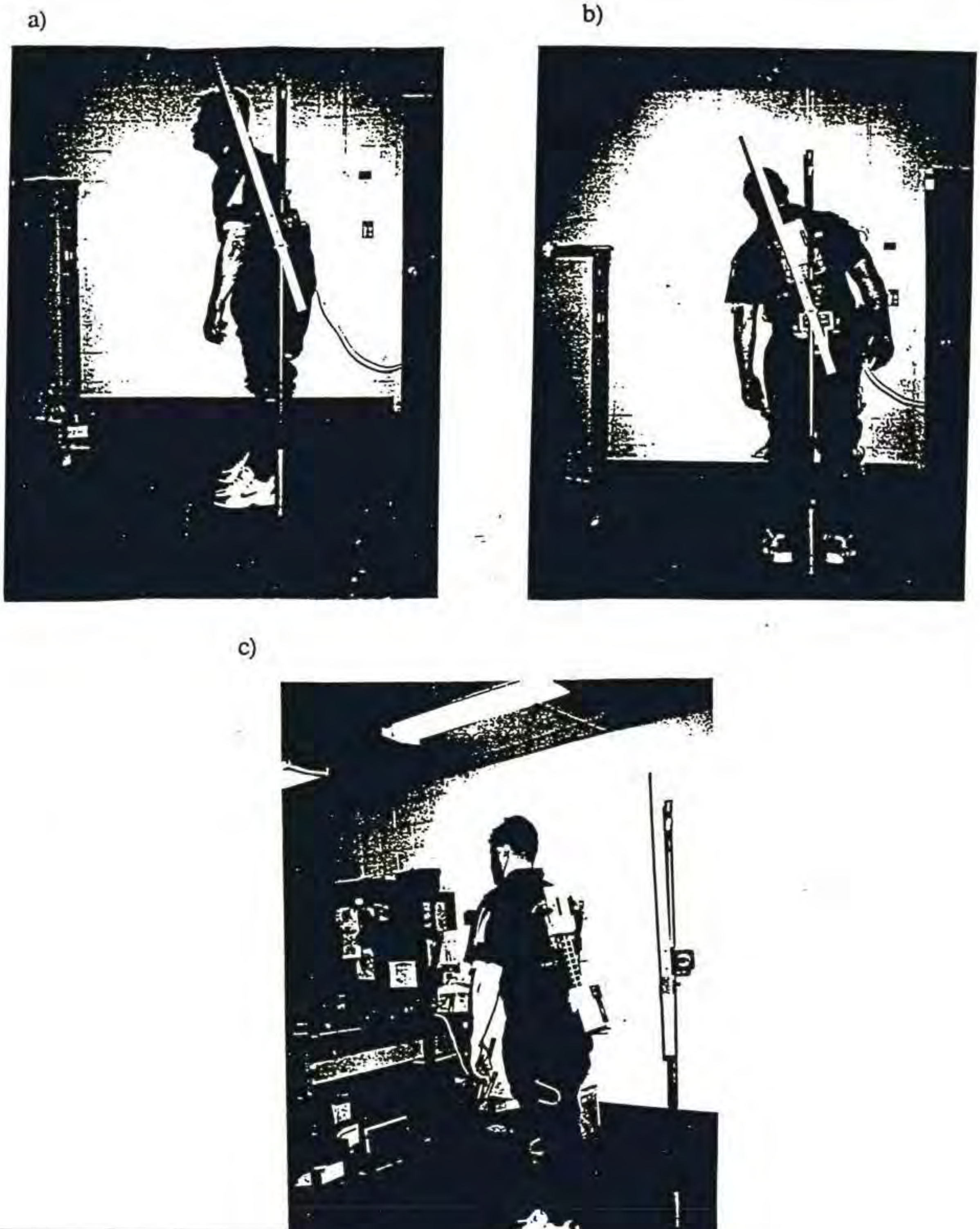

Figure 7. Illustration of data collection for a) subject in 20 degrees of trunk flexion, b) subject in 20 degrees of trunk lateral bending, and c) subject in 10 degrees of trunk torsion.

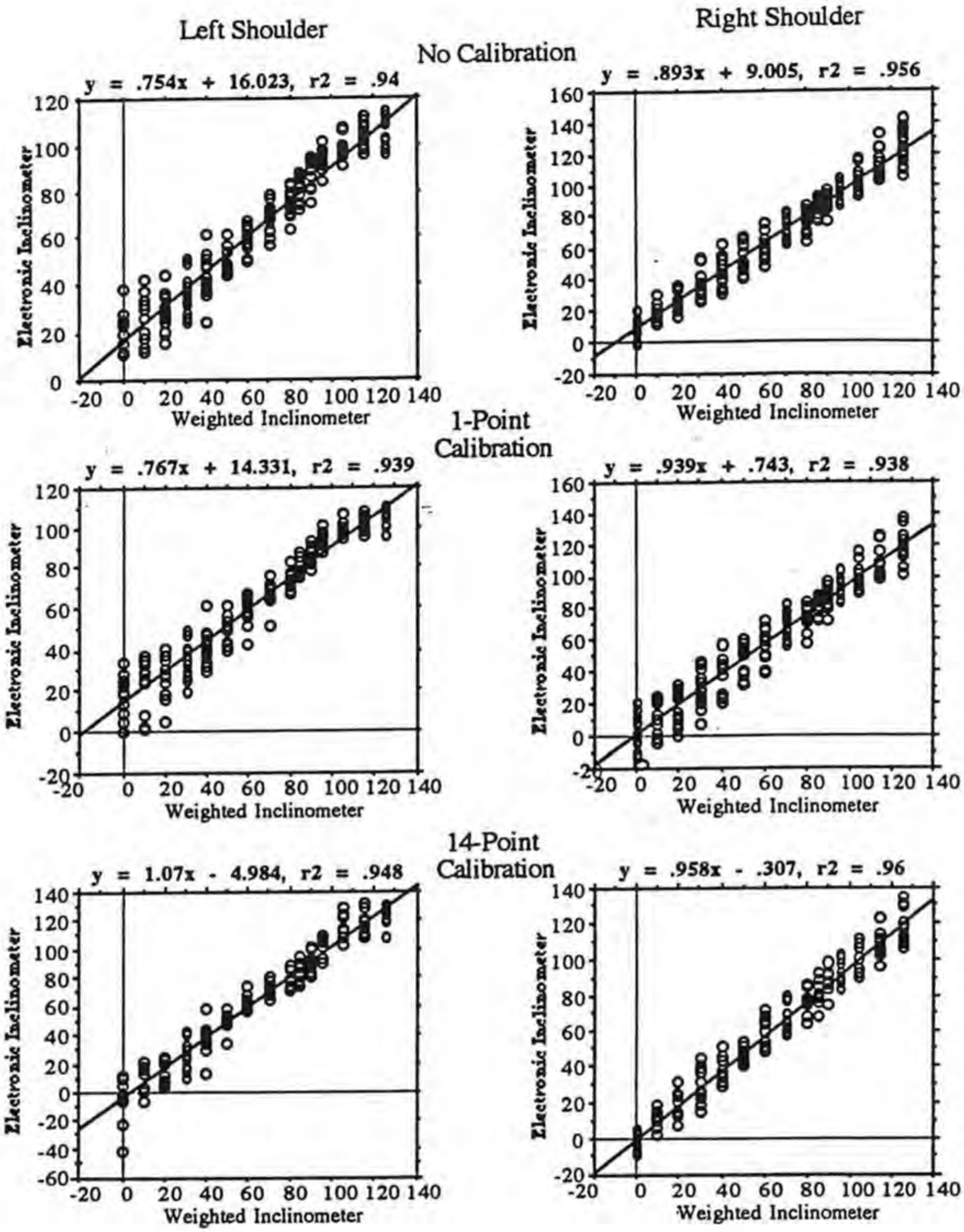

Figure 8. Shoulder flexion (deg.) predicted with the electronic inclinometers compared with shoulder flexion measured with a weighted inclinometer (5 subjects, 3 trials for no calibration, 2 trials for remaining plots).

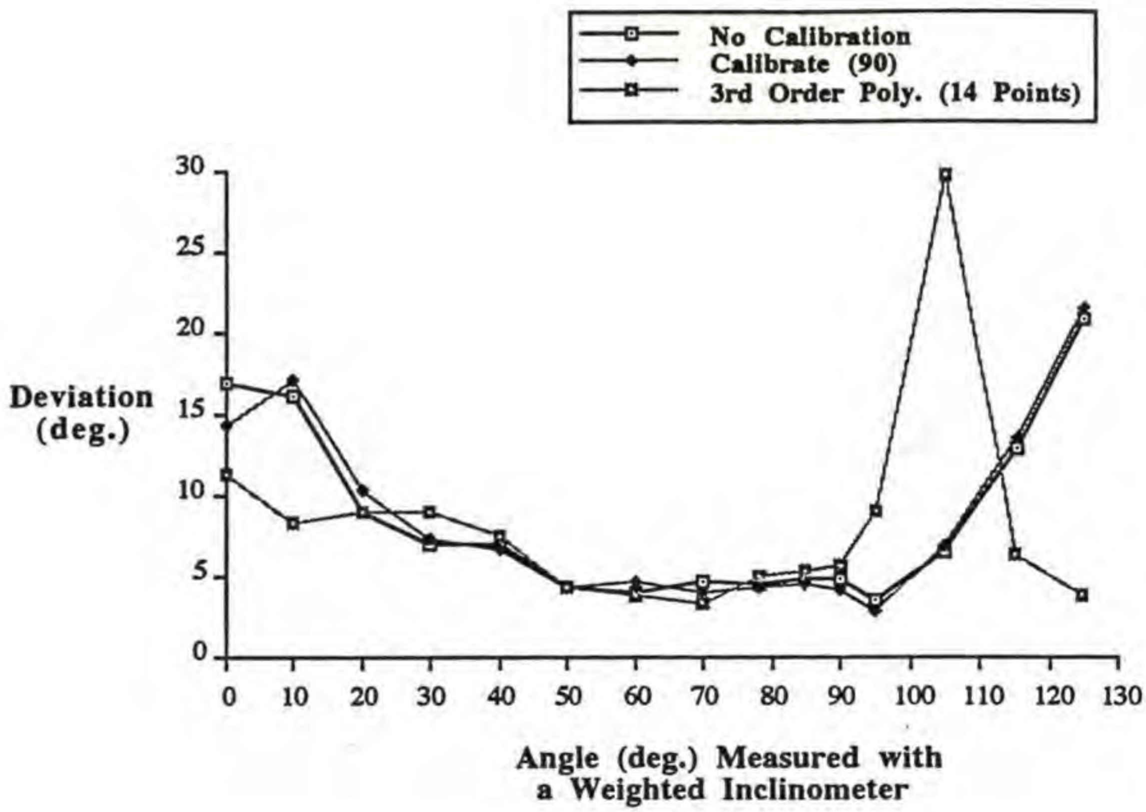

Figure 9. Average deviation (deg) in left shoulder flexion between measurements obtained with an electronic inclinometer and a weighted inclinometer (5 subjects, 3 trials for no calibration, 2 trials for remaining plots).

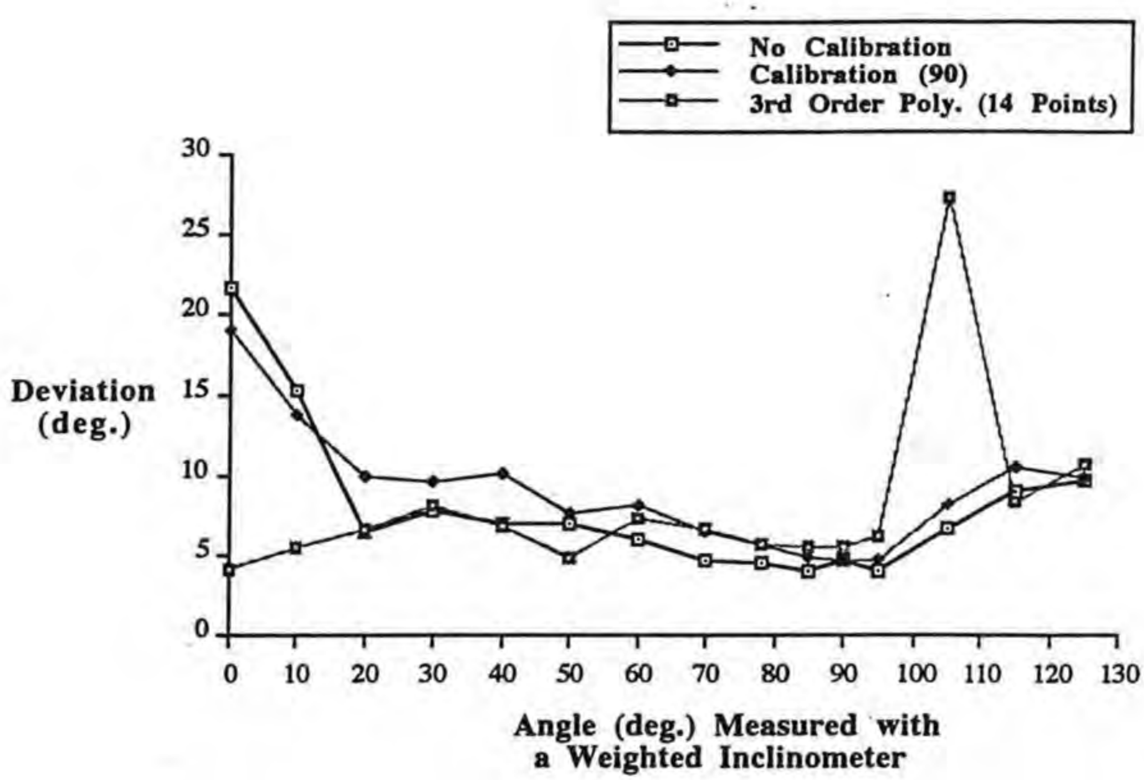

Figure 10. Average deviation (deg) in right shoulder flexion between measurements obtained with an electronic inclinometer and a weighted inclinometer (5 subjects, 3 trials for no calibration, 2 trials for remaining plots).

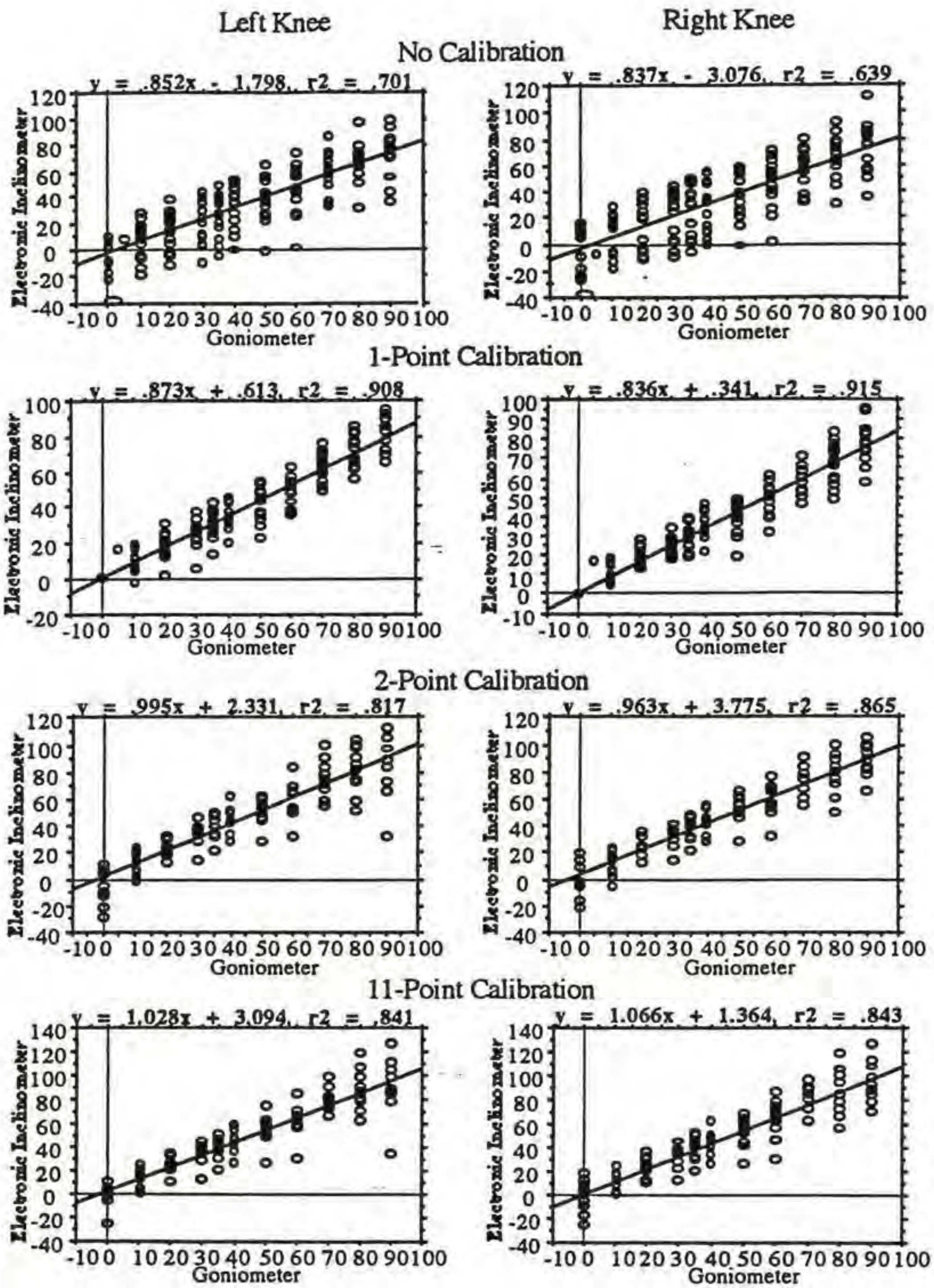

Figure 11. Knee flexion (deg.) predicted with the electronic inclinometers compared with knee flexion measured with a goniometer (5 subjects, 3 trials for no calibration, 2 trials for remaining plots).

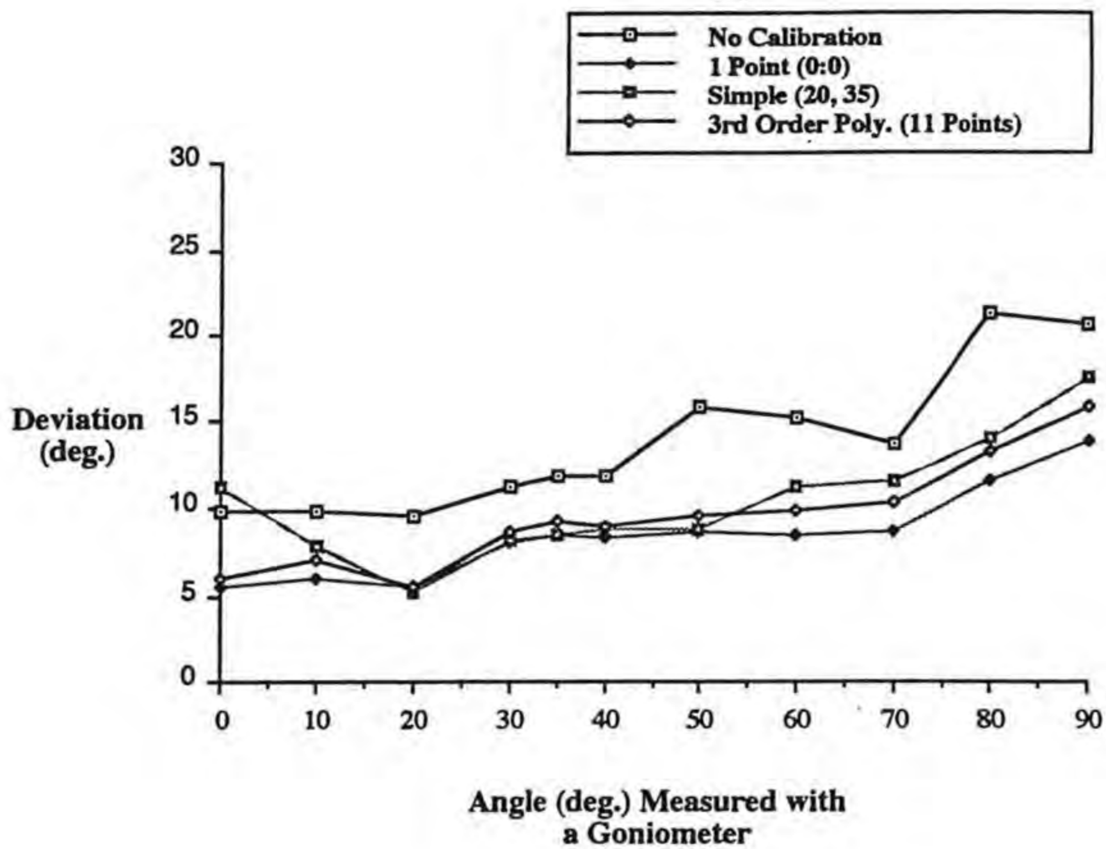

Figure 12. Average deviation (deg) in left knee flexion between measurements obtained with electronic inclinometers and a goniometer (5 subjects, 3 trials for no calibration, 2 trials for remaining plots).

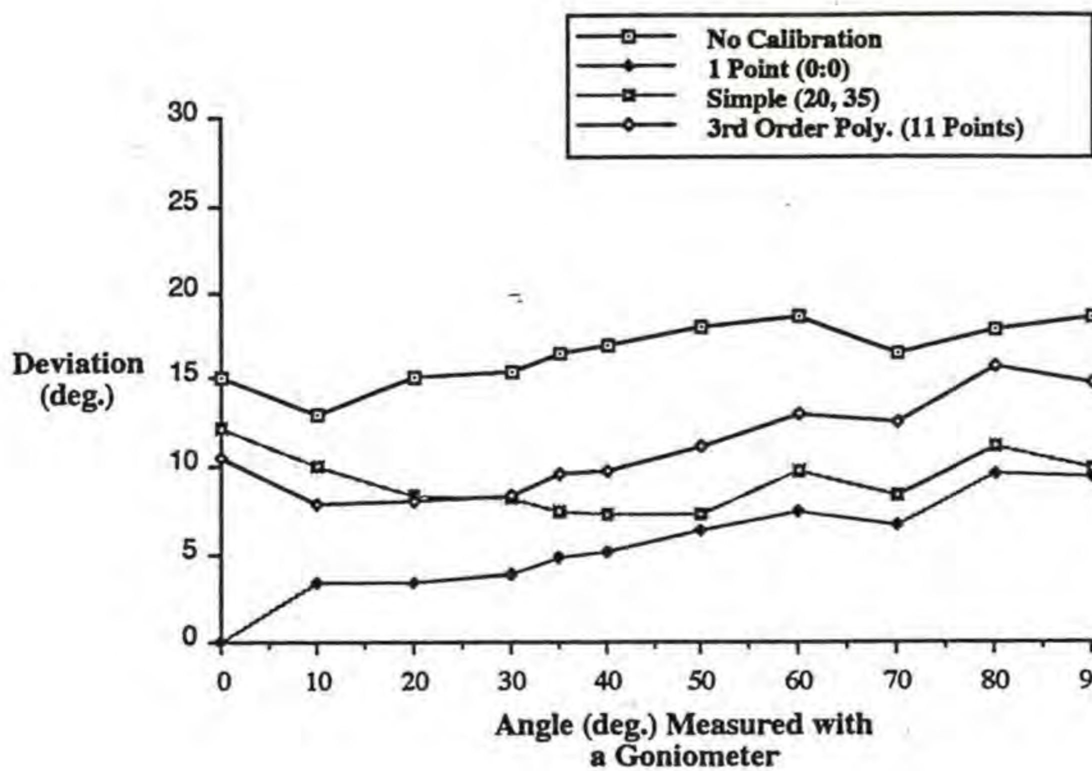

Figure 13. Average deviation (deg) in right knee flexion between measurements obtained with electronic inclinometers and a goniometer (5 subjects, 3 trials for no calibration, 2 trials for remaining plots).

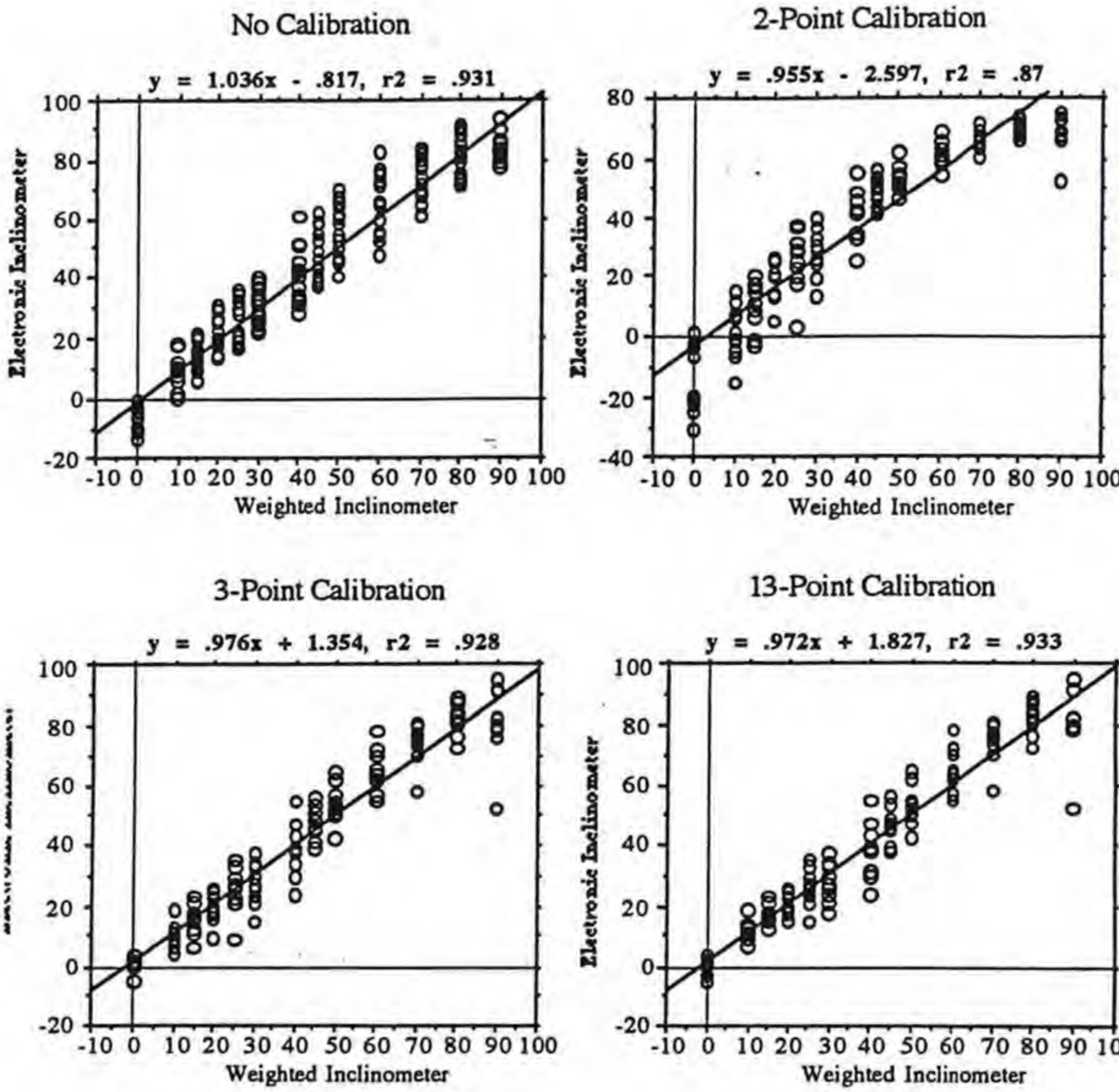

Figure 14. Trunk flexion (deg.) predicted with the electronic inclinometers compared with trunk flexion measured with a weighted inclinometer (5 subjects, 3 trials for no calibration, 2 trials for remaining plots).

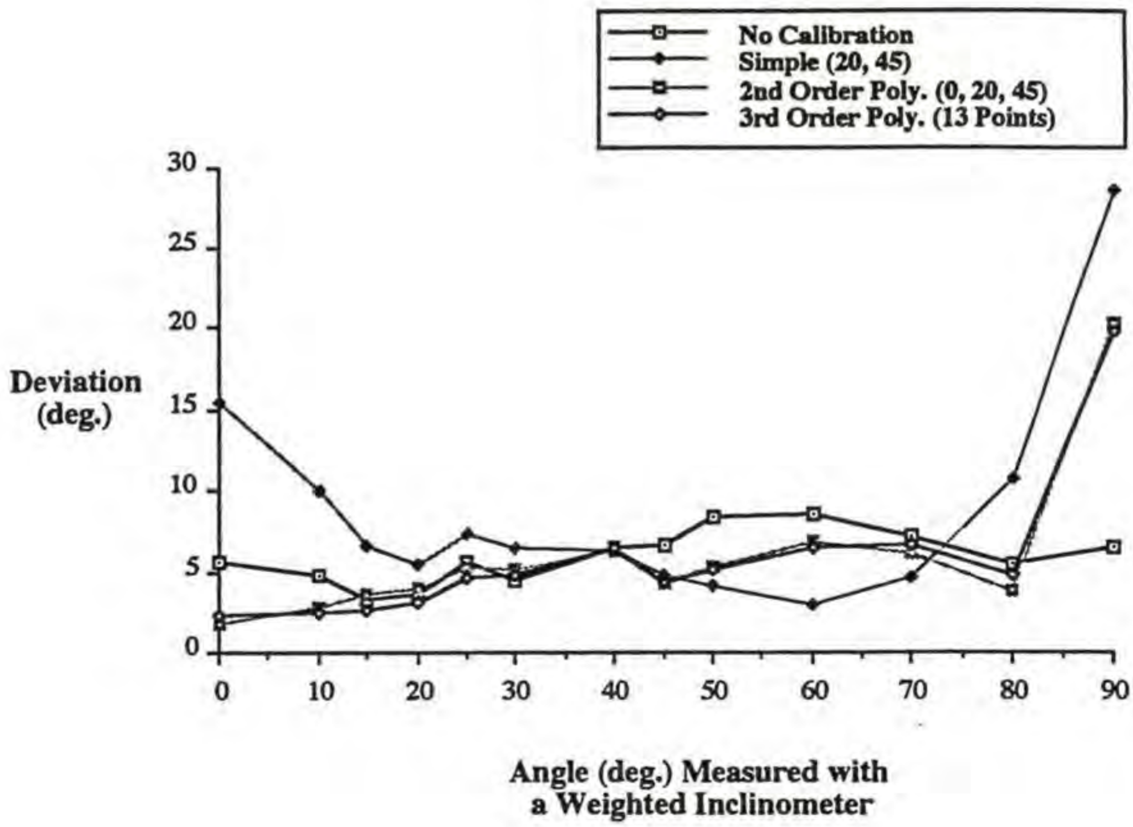

Figure 15. Average deviation (deg) in trunk flexion between measurements obtained with an electronic inclinometer and a weighted inclinometer (5 subjects, 3 trials for no calibration, 2 trials for remaining plots).

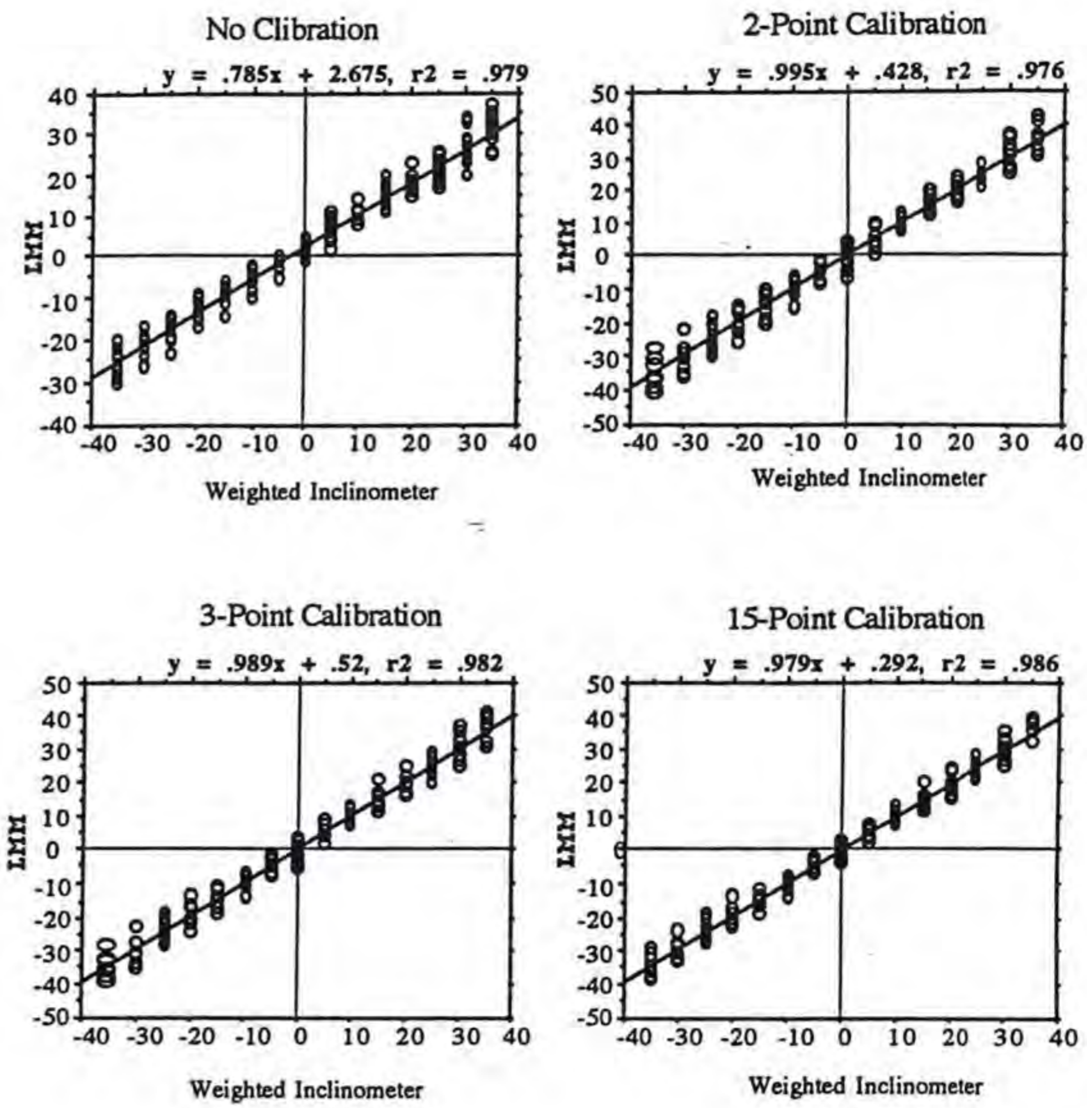

Figure 16. Trunk lateral bending (deg.) predicted with the LMM compared with trunk lateral bending measured with a weighted inclinometer (5 subjects, 3 trials for no calibration, 2 trials for remaining plots).

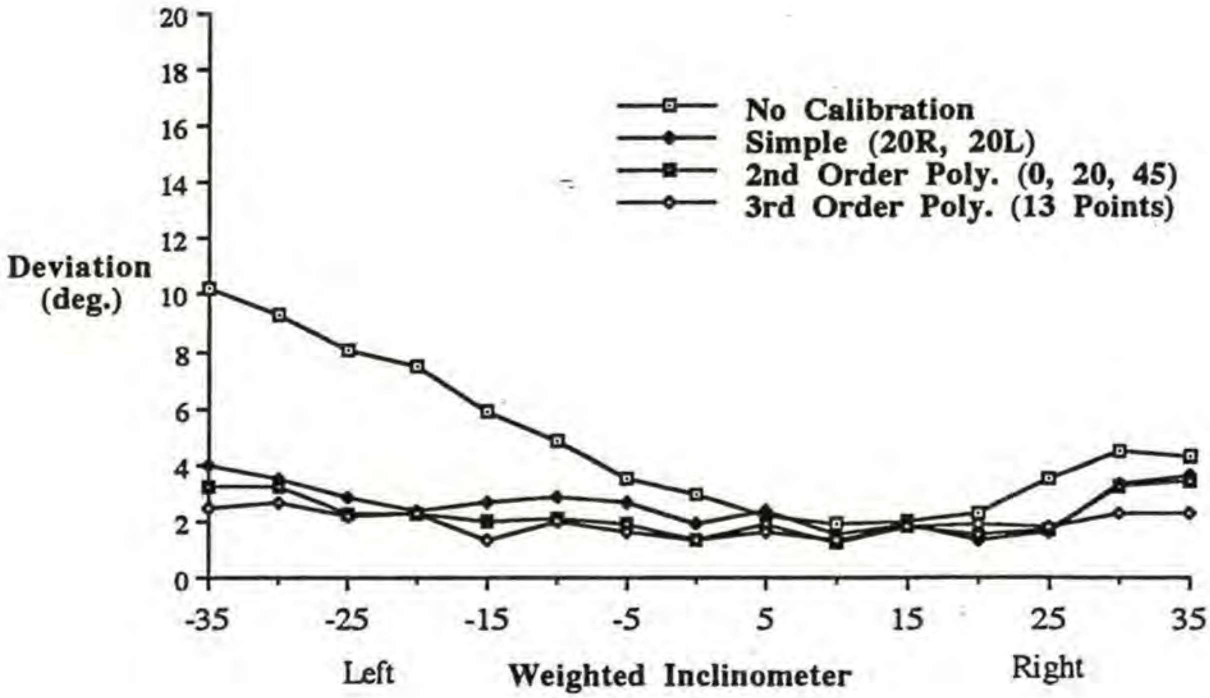

Figure 17. Average deviation (deg) in trunk lateral bending between measurements obtained with a LMM and a weighted inclinometer (5 subjects, 3 trials for no calibration, 2 trials for remaining plots).

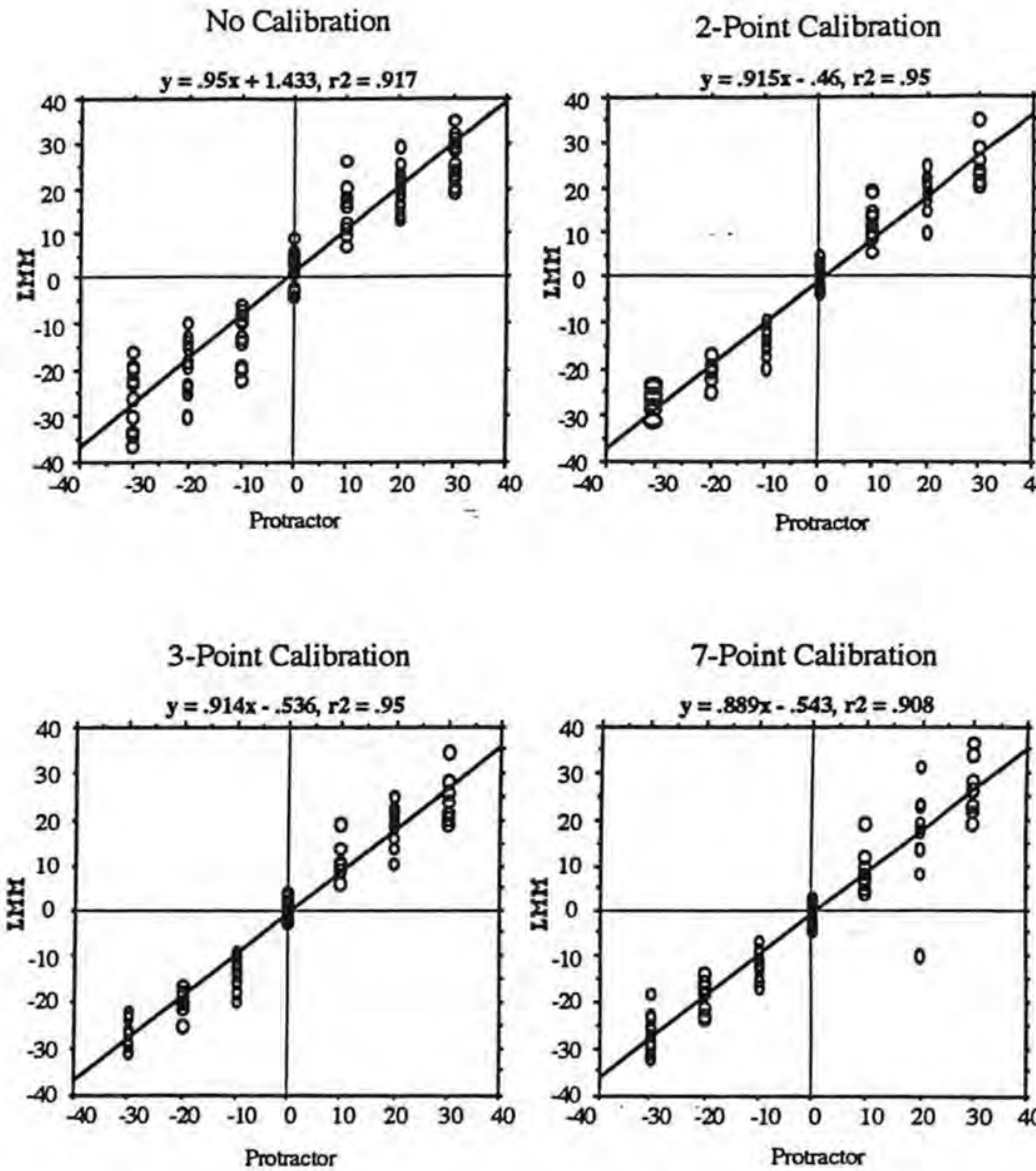

Figure 18. Trunk torsion (deg.) predicted with the LMM compared with trunk torsion measured with a protractor (5 subjects, 3 trials for no calibration, 2 trials for remaining plots).

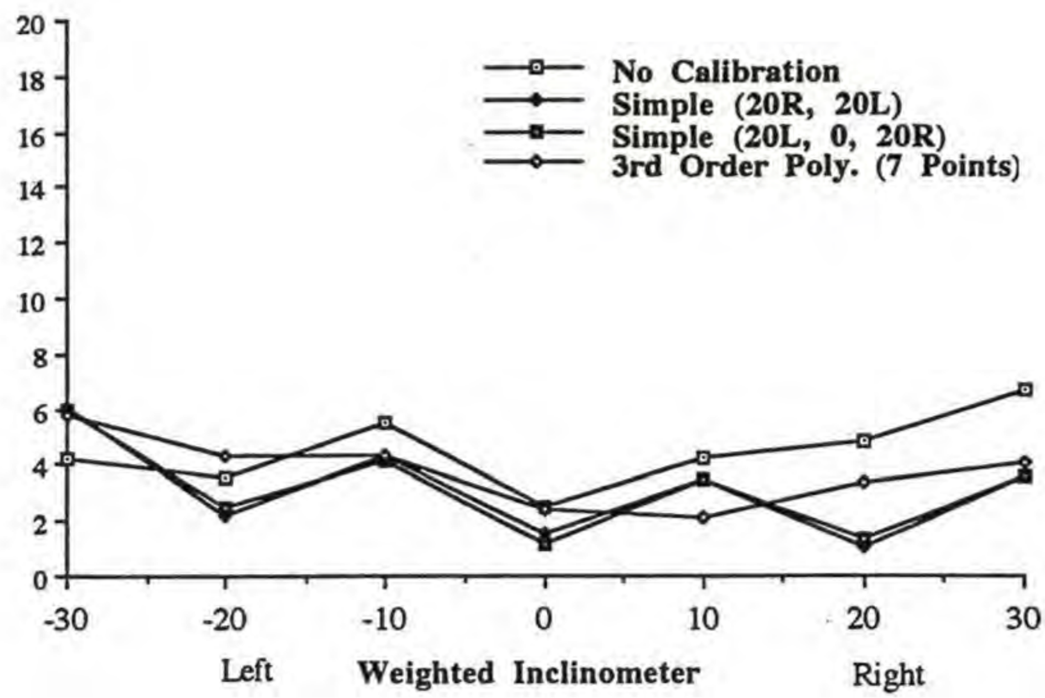

Figure 19. Average deviation (deg) in trunk torsion between measurements obtained with LMM and a protractor (5 subjects, 3 trials for no calibration, 2 trials for remaining plots).

CHAPTER III. A VALIDITY STUDY OF OBSERVATIONAL ASSESSMENTS OF BODY POSTURES DURING CONSTRUCTION WORK

A. INTRODUCTION

In spite of a high prevalence of musculoskeletal injuries in the construction industry and evidence that the physical demands of construction work often require awkward postures, heavy lifting and other forceful exertions, little quantitative data exist that describe the magnitude and frequency of these exposures for specific construction job tasks. This is partly because construction workers often perform multiple tasks with long variable work cycles, making the common cycle-based ergonomic assessment methods impractical.

Work sampling is a methodology that has been used by industrial engineers for approximately 60 years to quantify the proportion of time that workers or machines devote to different work activities (Pape, 1992). Modified forms of work sampling have been applied to studies of jobs where cycle-based ergonomic exposure assessment methods could not be used easily (e.g., Karhu et al., 1981; Mattila et al., 1993; Ryan, 1989; Wickstrom et al., 1985). For these types of assessments, observations about working postures or manual handling are usually made at fixed intervals throughout a representative work period. Observations are often made on categories of exposure, and the proportion of time recorded for a category of exposure is the ratio of the number of observations recorded for the category to the total number of observations.

PATH, a modified work-sampling method, has been developed specifically to characterize a variety of ergonomic exposures in construction and other non-repetitive work (see Buchholz et al., 1996 for a detailed description). With PATH, the proportion of time workers spend in awkward postures, handling loads, and performing manual materials handling (MMH) activities during individual job tasks, as well as the distribution of job tasks among workers, can be determined.

Observational methods, such as PATH, offer the advantages of providing data on multiple exposures collected simultaneously, over long time periods, and can be used with little disruption to the work. However, there are some uncertainties about the validity of observations for postural assessment. Some studies have found relatively poor-to-moderate agreement when measurements obtained with work sampling-type methods were compared to those obtained with direct measurement systems (e.g., Burdorf et al., 1992; De Looze et al., 1994).

The objective of this study was to examine the validity of PATH and a simplified version of PATH for the assessment of trunk, shoulder and knee postures in construction work, using direct-postural measurements as the reference. Comparisons are made between work-sampling and discrete direct measurements, work-sampling and continuous-direct measurements, and PATH and simplified PATH.

B. METHODS

1. Study Site and Subjects

The study took place at the New England Laborers' Training Academy in Hopkinton, MA. The training grounds closely resembled a typical construction site, equipped with a construction trench, utilities pit, truck, black-top surface and a variety of building materials (e.g., bricks, blocks, boards).

Five male college students were brought to the study site to simulate job tasks performed by construction workers. Each student signed an informed consent form prior to the study (Appendix I), was fitted with the electronic postural measurement system (see Chapter II), and performed 3 of 6 simulated construction job tasks. The order in which subjects performed each of the 3 tasks was randomly assigned.

2. Job Tasks

The six construction job tasks were designed to facilitate a wide range of body postures, and included work above the shoulders, as well as work below the knees. The construction job tasks were: 1) carrying wood beams into and out of a construction pit, 2) shoveling and moving crushed rock, 3) sweeping and shoveling dirt, 4) drilling concrete, 5) spreading mortar on concrete, and 6) moving bricks and concrete blocks (Figure 20). The tasks were considered representative of laborers' work based on information obtained in a survey of a union construction laborers and from researchers' field observations on highway construction sites. While the construction tasks were described in detail to each subject, the exact way in which individuals performed the task was not controlled, allowing conditions that more closely resembled actual construction work.

Six work areas were assembled for the study. A wheel barrow and shovel were placed near a pile of crushed rock for the task of shoveling and moving crushed rock. Sand was spread over a 7 m by 7 m black-top area, and a broom, wheel barrow and barrel were placed near the sand for the task of sweeping and shoveling dirt. Seventy-two bricks and 3 large 20 kg concrete blocks were placed in a pile on the ground for the task of moving bricks and blocks. Two rows of 8 concrete blocks were placed on a large wood frame (at ground level and at 2 m above ground level), and an electric power drill was left near the frame for the drilling of concrete. A pit was opened (approximately 3 x 3 m wide and 3 m deep), a ladder was placed in the pit, and a pile of 0.1 x 0.1 x 1.5 m boards was stacked approximately 10 m away from the ladder for carrying wood beams in and out of a pit. Eight concrete blocks, a gallon can of roofing cement and a trowel were placed together at a different location on site for the task of spreading mortar on concrete.

3. Work-Sampling Based Methods

Two work-sampling based methods were evaluated: PATH and a simplified version of the PATH method. Both methods required observers to record postures in categories that had been modified from the OWAS (Karhu et al., 1977; 1981). These included 3 categories of upper arm posture (arms below shoulders, 1 arm at or above shoulder height, both arms at or above shoulder height), 9 categories of leg posture (standing with knees bent < 35 degrees, standing with 1 leg in air, standing with knees bent ≥ 35 degrees, walking, squatting, kneeling, sitting on chair, sitting on ground, and climbing/descending), and 5 categories of trunk posture (neutral, flexion ≥ 20 and < 45 degrees, flexion ≥ 45 degrees, lateral bending ≥ 20 degrees or torsion > 20 degrees, and flexion ≥ 20 degrees with lateral bending or torsion ≥ 20 degrees). The judgment of trunk postures involved estimating the position of the shoulders relative to the hips in the sagittal (trunk flexion), frontal (trunk lateral bending) and transverse (trunk torsion) planes (Chapter I, Figure 3).

Both methods involved recording observations using a PATH template and scannable data collection sheets. Categories of variables listed on the data collection template included: worker identification number, task, body postures, weight handled, MMH activities, general activities, task specific activities, tools/equipment and hand postures. For the full PATH method, all relevant variables on the template were considered during each observation. For the simplified version of PATH, the observer used the same template but was required to record only the worker identification number, task performed and body postures during each observation.

Load weight, MMH activities, general activities and grasp types were categorized in the usual manner, using the standard PATH data collection template (Chapter I, Figure 2). The task-specific activity categories were customized for the tasks and included: shoveling, using wheelbarrow, dumping rock, sweeping, moving barrel, using dust pan, changing drill bit, connecting drill to power supply, opening/closing bucket of mortar, mixing/scooping mortar in bucket, applying mortar to concrete and miscellaneous. Tools and equipment listed on the template included: shovel, wheelbarrow, power drill, drill bit/chuck, trowel, bucket, broom, concrete block, brick, boards, bricklayer wheelbarrow, dust pan and other. Prior to data collection, observers familiarized themselves with data collection templates and were given a demonstration of each of the tasks.

The observers were experienced PATH coders, had received the same 30-hour course in PATH data collection and had collected PATH data together on several occasions. During previous studies, tests of inter-observer reliability for PATH posture codes were usually high, with the proportion of agreement > 0.90 for shoulder postures, > 0.80 for leg postures and > 0.70 for trunk postures (Buchholz et al., 1996).

4. The Reference System

The use of the electronic direct postural assessment system, consisting of 7 electronic inclinometers and a LMM (see Chapter II), and video tape analysis provided the reference measurements. The electronic inclinometers (Desktop Laboratories, Inc., 1996) were used to measure shoulder postures, knee flexion, and trunk flexion, and the LMM (Chattanooga Group, Inc., 1996) was used to measure trunk side bending and torsion. The analysis of video tape was used to identify the presence of standing, walking, kneeling and sitting postures. The postural exposure of knee flexion of at least 35 degrees was determined by evaluating the electronic inclinometer data for the knees during the standing postures identified with the video tape.

One researcher operated the electronic inclinometers and LMM, while another researcher operated the video camera. The video was recorded for the subject continuously during the task. The video analysis included frozen-frame evaluation of leg postures the moment that each work sampling observation was made (with auditory cues) and the simulated real-time analysis software (Keyserling, 1986) to estimate leg postures over the duration of each task. The simulated real-time analysis required an observer to press the appropriate computer keys when posture categories changed as the video tape was played. The software provided time intervals for each posture category, as well as its frequency of exposure (Table 16).

5. Fitting

Each subject was fitted with a pair of custom-designed coveralls that contained wiring for the electronic inclinometers and a portable data logger (Figure 21). The electronic inclinometers, LMM and knee pads were then secured over the coveralls. The electronic inclinometers were strapped tightly in line with the subject's arms and perpendicular to the subject's legs with Velcro, elastic bands and tape (Figure 22). One inclinometer was attached to each upper arm slightly lateral to the biceps and in line with the arm. Two inclinometers were attached to the lateral sides of the upper and lower legs and were approximately horizontal when the subject stood with the legs straight. The portable data logger (Onset Computer Corporation, 1993) was secured inside the coveralls. The LMM was secured over the coveralls in line with the lumbar region of the spine. An electronic inclinometer was secured to the upper base of the LMM over the thoracic region of the spine and was close to horizontal when the subject stood erect. The LMM digital telemetry transmitter was worn on a belt.

6. Calibration of Electronic Postural Measurement System.

Individual calibration of the electronic inclinometers for arm postures and trunk flexion was not required. Equations used in Appendix II, Figure II-5 were used to predict arm postures (relative to the shoulders) and trunk flexion from the voltages produced by the inclinometers.

The calibration of the electronic inclinometers and LMM for each subject required recording electronic measurements at body angles measured with manual instruments. A manual goniometer, aligned with the midsection of the lateral portions of the knee and upper and lower legs, was used to measure knee flexion. A weighted inclinometer was aligned with the spine in the coronal plane to measure trunk lateral bending. For the calibration measurements of trunk torsion, the subject stood with the ankles centered over a large protractor, the hips were fixed in line with the ankles, and the angles measured with the protractor were those between the hips and the shoulders in the transverse plane.

To calibrate the electronic inclinometers, measurements were made with the knees flexed 20 and 35 degrees. To calibrate the LMM, measurements were made with the trunk bent laterally 0 and 20 degrees to each side and twisted 20 degrees to each side (Figure 23). The calibration procedures were those that were simple and produced reliable measures of PATH posture categories during a laboratory study (see Chapter II, Tables 4, 7, 10, 12 and 14).

For calibration of the electronic inclinometers, data were collected at 50 Hz for 2 seconds while the worker held each of the knee postures. For the calibration of the LMM, data were collected at 60 Hz for 3 seconds for each of the trunk postures. The electronic-inclinometer data files were downloaded into a personal computer in hexadecimal format. From the calibration of individual measurements, regression analysis provided individual prediction equations for the degree of knee flexion based on voltage outputs of the inclinometers, and trunk lateral bending and torsion from the LMM measurements (Chapter II).

7. Data Collection

Before each task, the subject was given a set of written and oral instructions outlining the construction task to be completed. The tasks were performed in random order and all work areas were assembled prior to the study so that the observers had very little time to anticipate which task was to be performed.

While each subject performed a task, 2 observers made PATH observations at 1 minute intervals at different times. PATH observations were staggered between observers, so that one PATH observation was recorded every 30 seconds. A third observer made simplified PATH observations every 30 seconds at the same moment that the PATH observations were made. For each observation, a verbal count down of "5, 4 , 3, 2, 1, CODE" was given, and the observers recorded the information on "CODE". Observers remained approximately 10 m from the subjects during data collection.

Inclinometer data were collected continuously throughout the task (at 2 Hz for 28 seconds of each half minute and at 50 Hz for a 2 second interval that included that instant of PATH and simplified PATH coding). The increased sampling rate improved the precision of the electronic inclinometers at the instant the work-sampling measurements were made (electronic measurements from 0.25 seconds before to 0.25 seconds after the observation were averaged). These electronic inclinometer measurements were downloaded from the data logger to a personal computer after each of the tasks were completed.

LMM data were collected at 60 Hz for 10 second periods beginning 5 seconds before and ending 5 seconds after each observation, providing measurements of trunk lateral bending and torsion for one-third of each task. Data were transmitted directly from the LMM to a lap top personal computer via digital telemetry.

Each worker was also videotaped continuously throughout the task so that leg postures (kneeling, squatting, walking, climbing or sitting) could be later identified. The evaluation of the video included a frozen-frame analysis method and simulated real-time method (Keyserling, 1986). The frozen-frame video analysis required the video to be paused on the auditory cue of "CODE" that corresponded to the instant that the work-sampling measurements were taken, and the presence of standing, kneeling, squatting or walking postures on the video tape was recorded. For the real-time simulated analysis, the sequence and duration of these leg postures were recorded continuously throughout the tasks (Figure 24).

The video tape, electronic measurements and work-sampling observations were synchronized with a stopwatch so that measurements could be compared directly between the methods. The stopwatch and data logger were activated simultaneously. The stop-watch was used to determine the appropriate time to activate the LMM.

Each task was performed for approximately 15 minutes. After the task was completed, the data in the portable data logger were downloaded to a personal computer in hexadecimal format. The data logger and the stopwatch were then re-activated, and the subject proceeded to the next task.

8. Data Management

Calibration Data

A Turbo PASCAL program (Borland International, Inc., 1992) was used to convert the electronic inclinometer data for knee flexion from hexadecimal to ASCII format. Each calibration file was then imported into Excel (version 4.1) and the average of the 100 voltage measurements taken for each 2 second interval was calculated. The average voltages for each posture were then imported into Statview for the Macintosh (version 1.04) and the calibration equations used to predict postures from the voltage outputs were calculated with regression analysis. For each knee, the difference of the upper and lower leg electronic inclinometer voltage readings for 20 and 35 degrees flexion was used to develop a simple-linear equation in which knee flexion was predicted from the difference in voltage readings.

The LMMI calibration files were converted into ASCII format and imported into Excel. The average measurement of lumbar lateral bending or torsion was calculated for each measured value of trunk lateral bending and torsion. These data were also imported into Statview for the Macintosh (version 1.04). Measurements at 0 and 20 degrees (right and left) trunk lateral bending were used to develop a linear equation in which trunk lateral bending was predicted from measured lumbar lateral bending. Measurements at 20 degrees right and left torsion were used to develop a linear equation allowing trunk torsion to be predicted from lumbar torsion.

Direct -Measurement Data

The electronic inclinometer and LMMI ASCII files for each job task were imported into Excel. The appropriate prediction equation were then applied to each of the measurements to obtain the body posture measurements. These included the knee flexion and trunk lateral bending and torsion equations developed from the calibration of individual subjects and the 3rd-order polynomial prediction equations for arm and trunk flexion based on no individual calibration (Appendix II, Figure 5). The posture prediction equations for each subject and posture are shown in Appendix IV (Tables IV-1 and IV-2).

Observational Data

The raw observational work-sampling data were manually keyed into an Excel spreadsheet and were converted into an ASCII file. The posture frequencies for each subject during each task were calculated with SAS (SAS Institute, Inc., 1992).

Comparisons between Observations and Discrete Direct Measurement

One data base was developed to allow comparisons to be made among methods at discrete intervals. This data base contained postural data for each of the observations made during the tasks. For this, electronic data collected from 0.25 seconds before until 0.25 seconds after each observation was averaged. The standing postures recorded in the frozen-frame video analysis were cross-referenced with electronic inclinometer data for the knees to distinguish between neutral and flexed standing. The reference and work-sampling data were matched at each observation.

Comparisons between Observations and Continuous Direct Measurement

A second data base was constructed to allow comparisons to be made between the work-sampling data and the continuous reference data. The electronic inclinometer data that were collected at 50 Hz were averaged into four 2-Hz measurements, and the frequencies of shoulder, knee and trunk flexion categories were determined for the entire continuous sampling period taken at 2 Hz for each task. The average frequency of trunk lateral bending and torsion categories predicted with the LMM were also used for the entire sampling period (1/3 of each task). For the video analysis, frequencies of each leg posture determined with the simulated real-time analysis were included in the data base. The standing postures that were identified with the simulated real-time analysis were cross referenced with electronic inclinometer data to distinguish between neutral and flexed leg postures. For each subject-task combination, the frequency of each exposure and the time over which data were collected were included in the data base.

For the work-sampling based methods, the exposure frequencies and the number of observations for each subject-task combination were calculated and placed in this data base. For this analysis, the PATH posture categories of trunk posture were reorganized so that the frequency of trunk flexion, lateral bending and torsion could be evaluated separately (i.e., observations of trunk flexion and lateral bending or torsion were counted appropriately in the separate evaluations of trunk flexion, lateral bending and torsion). A schematic of the data management procedures is shown in Figure 25.

5. Data Analysis

Observations vs. Discrete Direct Measurement

Based on measurements made for individual observations, the frequency of different trunk-, arm- and leg-posture categories recorded with both observational work-sampling approaches were compared to those recorded with the electronic inclinometers, LMM and video. The Chi-Square statistic was used to determine whether the frequencies of exposure categories differed among the methods. Two statistics were used to evaluate the agreement among the methods: proportion of agreement and kappa (k) coefficient, a measure of agreement which excludes the influence of chance (described in Chapter II). Contingency tables listing the exposure frequency categories for the reference system (electronic and video measurements) and work-sampling methods were examined to identify the posture categories resulting in the most frequent disagreement.

Observations vs. Continuous Direct Measurement

Using the second database, the observational data were compared to the continuous reference measurements made on the same tasks. The total time-weighted exposure frequency across all subjects and tasks was calculated for the direct and video measurements. The total observation-weighted exposure frequency across all subjects and tasks was calculated for the work-sampling methodologies: The observation-weighted exposure frequency is the equivalent of a time-weighted exposure estimate in that the measure is based on the number of observations made and frequency of exposure for each task. The 95%-confidence intervals were calculated for the estimates of exposure frequency for the work-sampling data, and these were compared to the measurements obtained with the reference system. The reference measure was considered to differ significantly when the frequency of the measured exposure fell outside the 95%-confidence interval of the observational measures.

C. RESULTS

1. Shoulder Postures

Observations vs. Discrete Direct Measurement

For the analysis of individual observations made on the arm postures, there were 463 electronic inclinometer, 461 simplified PATH and 457 PATH observations. There were no significant differences in the frequency of exposure to the three shoulder posture categories among the three methods (Chi Square on 4 d.o.f. = 3.1, p = 0.54). The frequency of arm postures above shoulder height was 13.5% for the electronic inclinometers and 15% for each of the work-sampling methods (Figure 26).

Agreement in the frequency of arm-posture categories was extremely high for all three methods (P(a) $\geq$ 0.93 and $k \geq 0.74$), with the strongest agreement between the electronic inclinometers and simplified PATH method (Table 17). Measurements between the electronic inclinometers and work-sampling methods contradicted one another most frequently when the electronic inclinometers recorded one arm at or above shoulder height. In this case, 20% (4 of 20) of the simplified PATH observations and 40% (8 of 20) of the PATH observations were in a different category, equally divided between both arms above and below the shoulders. Disagreement between the work sampling and electronic inclinometer measurements was quite rare (5% or less) for the other shoulder postures (Tables 18 and 19).

Observations vs. Continuous Direct Measurement

The frequency of arm posture categories closely approximated the time-weighted frequency of arm-posture categories measured continuously with the electronic inclinometers. The frequency of exposure to arm postures below shoulder height obtained with both work sampling approaches was within 1% of the exposure frequency obtained with the electronic inclinometers. The frequency of exposure to arm postures at or above shoulder height was identical for the electronic inclinometers and the simplified PATH. The frequency of exposure to arm postures at or above shoulder height obtained with PATH was within 2% of the frequency obtained with the electronic inclinometers (Table 20).

2. Knee Postures

Observations vs. Discrete Direct Measurement

There were 463 reference, 462 simplified PATH and 459 PATH observations made on the leg postures. Overall, there were significant differences in the frequency of exposure to leg-posture categories among the methods (Chi Square on 12 d.o.f. = 24.3, $p = 0.02$). While the measured frequency of kneeling and climbing postures were almost identical among the methods, larger differences were observed in the frequency of walking, knee flexion and neutral leg posture. When the frequency of exposure to each of the individual leg-posture categories was compared among the methods, there were significant differences for only exposure to standing with legs straight (Chi Square on 2 d.o.f. = 12.5, p = 0.002). When compared to the knee flexion the electronic inclinometers, the work-sampling methods over-estimated the frequency of standing with legs straight, and slightly under-estimated walking and knee flexion. The frequency of leg postures estimated with simplified PATH was consistently closer to the reference than PATH (Figure 27).

Inter-method agreement for the coding of leg postures was high (P(a) ≥ 0.81 and *k* ≥ 0.75), with the highest agreement between the reference and simplified PATH methods (Table 21). The reference and work sampling observations were in disagreement most frequently when knee flexion was recorded by the reference system. For this, 18% (16 of 90) of the simplified PATH observations were recorded as neutral and 41% (36 of 88) of the PATH observations were recorded as neutral (Tables 22 and 23). Walking identified from the video tape was classified as neutral 6.8% of the time with simplified PATH and 13.2% of the time with PATH. Additionally, standing postures identified in the video analysis, were misclassified as knee flexion or walking 11% of the time with PATH.

Observations vs. Continuous Direct Measurement

The frequency of leg-posture categories measured continuously for the entire task with the reference system were generally close to measurements obtained with simplified PATH. For the reference measurements of kneeling and climbing, the overall time weighted exposure measurements were within 1% of the simplified-PATH measurements. For neutral leg postures, however, the continuous reference measurements fell below the 95%-confidence interval of the simplified-PATH estimation. For knee flexion, the continuous reference measurements exceeded the 95%-confidence interval of the simplified-PATH estimation (Table 24).

The frequency of leg-posture categories measured continuously for the entire task with the reference system were less likely to fall within the 95%-confidence interval of the PATH leg posture frequency estimates. The reference measurements fell outside the PATH frequency estimates for walking, knee flexion and neutral leg postures. PATH measurements overestimated the frequency of exposure for neutral postures, and underestimated the exposure frequency of knee flexion and walking (Table 24).

3. Trunk Posture

Observations vs. Discrete Direct Measurement

For the evaluation of individual observations, there were 463 reference and simplified-PATH measurements and 457 PATH observations for trunk postures. The frequency of trunk postures varied significantly among the methods (Chi Square on 8 d.o.f. = 38.0, $p = 0.001$). When the frequency of exposure to each trunk posture category was compared among the methods, significant differences were found in the frequency of trunk lateral bending (Chi Square on 2 d.o.f. = 46.1, $p = 0.001$) and torsion (Chi Square on 2 d.o.f. = 10.8, $p = 0.005$). The smallest differences were observed in the measured frequency of mild flexion, with differences among the methods within 2%. For the neutral and mildly flexed trunk postures, frequency estimates made with simplified PATH were slightly closer to the reference measurements than the PATH frequency estimates; while for severe flexion, the opposite was true. The frequencies of trunk lateral bending or torsion, and flexion in combination with lateral bending or torsion were underestimated with both work-sampling methods (Figure 28).

The agreement among methods was moderately high ($P(a) \geq 0.68$ and $k \geq 0.51$), and comparisons to the reference measurements were more favorable for simplified PATH than PATH (Table 25). The reference and work sampling observations contradicted one another most frequently when the reference measures recorded lateral bending or twisting postures. For lateral bending or twisting, approximately 70% of the simplified PATH and PATH observations were coded as neutral. When the reference system recorded trunk lateral bending or torsion in combination with flexion, 38% of both types of work sampling measurements were recorded as severe flexion (Tables 26 and 27).

Observations vs. Continuous Direct Measurement

The frequency of neutral and flexed trunk-posture categories were similar between the work sampling and continuous reference measurements. However, for severe flexion, the reference measurements were below the 95%-confidence interval of the simplified-PATH estimate. The reference measurements of trunk lateral bending and torsion exceeded the 95%-confidence intervals of the exposure estimates for both work-sampling methods (Table 28).

D. DISCUSSION

1. Validity of Discrete Interval Observations

The inter-method agreement among the electronic inclinometers, LMM and video and work-sampling measurements was, for the most part, high for the assessment of body postures during the simulated construction tasks. These results were more favorable than those of the few other studies that have compared observational measurements made in real-time with direct measurements (Burdorf et al., 1992; De Looze et al., 1994; Leskinen et al., 1997).

Leskinen et al. (1997) compared the Portable Ergonomic Observation (PEO) method with an optoelectronic 3-dimensional postural analysis system for evaluating body postures during laboratory-simulated work tasks. The PEO method required observers to use a hand-held computer to continuously register a worker's changes in body posture and activities (Fransson-Hall et al., 1995). The authors found that there was high agreement between the PEO method and optoelectronic system for characterizing the duration of clearly identifiable static postures but found poor agreement among the methods for dynamic work situations.

These results may not be indicative of other observational assessment methods such as work sampling. Monitoring exposures with PEO requires continuous vigilance and is likely to be more difficult than characterizing exposures with work sampling. Work-sampling types of methodologies require the observer to record only exposures that occur at the instant of observation, allowing brief periods of recovery time between observations.

Burdorf et al. (1992) assessed the validity of a widely used observational work-sampling technique, OWAS (Karhu et al., 1977; 1981), for characterizing trunk postures during dynamic and sedentary jobs. An electronic inclinometer was attached directly on the spine at L2-L3 and measured inclination for this region of the back. Large differences were found in trunk bending greater than 20 degrees for individuals and observers consistently over-estimated the frequency of trunk flexion. When worker exposure was dichotomized by less than and greater than 30% work-time spent with the trunk bent, moderate agreement was found between the two methods.

One potential limitation of the study noted by the researchers involves the difference in exposure classification definitions between the methods. For the observations, the angle of trunk inclination was defined as the angle between a straight line connecting the pelvis and shoulders and the vertical, while the electronic inclinometer measured the angle between the lumbar spine and vertical. One explanation for the higher frequency of observed moderate trunk postures might be that the shoulders, or the thoracic and cervical vertebrae contributed to the trunk inclination during moderate trunk flexion.

De Looze et al. (1994) examined the validity of another postural work-sampling technique, TRAC (van der Beek et al., 1992), during a laboratory-simulated manual materials handling task. TRAC measurements were compared to those of a two-dimensional diode-based analysis system positioned to minimize distortion and a video analysis system. The authors found that inter-method agreement was high between reference observational methods for distinguishing kneeling versus standing postures but was low for trunk, arm and other knee postures. The authors found that over one-half of the disagreements related to trunk posture occurred when the trunk was changing position. Here again, one potential reason for the disagreement between the measurement methods may involve slight differences in the operational definitions of trunk, arm and knee postures between the two methods (i.e., if markers are placed on joints that were not exactly consistent with the visual landmarks used for TRAC). It should be noted that the tasks evaluated in this study were extremely dynamic, requiring continuous body motion.

The validity of PATH for classifying trunk postures was previously investigated (Buchholz et al., 1996). In this study, the reference method of measurement was the simulated real-time analysis system. PATH observations were made on laborers and carpenters who were video-recorded simultaneously. The percentage of time that the laborers and carpenters were observed in the trunk-posture categories differed markedly between the two methods (differences of 4% -24% for the trade specific data and 5%-15% for the pooled data). These differences would have been expected by chance alone, due to the small numbers of observations made on each trade. There may also have been errors in reference measurements, which required performing 3-dimensional posture analysis from video tape. This evaluation was performed during the development of the PATH method, and the observer had little training or experience in using the method in the field. The validity of PATH for evaluating arm and leg postures was not examined in this study.

In the present study, much effort was directed at overcoming the methodological study limitations mentioned above. Each observer was trained and experienced in PATH coding. Much effort was also devoted to ensuring that the reference and observational measurements had the same or similar operational definitions. For example, the LMM measurements of lumbar lateral bending and torsion were used to predict the position of the shoulders to the hips in the coronal and transverse planes. The tasks in this study, having both dynamic and static characteristics, were carefully designed to represent those observed on construction sites.

The strongest agreement among the three methods was found in the categorization of shoulder postures. Analysis of the shoulder-posture frequency among methods demonstrated that the observational data closely approximated the reference measurements, with the largest discrepancies for the reference measurements of 1 arm at or above shoulder height. Misclassification of exposure categories appeared random (the frequency of misclassification of postures below shoulder height was similar to the frequency of misclassification of shoulder postures above shoulder height) and was extremely rare. The observed arm posture frequencies were also quite similar to the continuous reference measurements for all arm-posture categories.

While there were significant differences in the frequency of leg-posture categories among the methods, the frequency of exposure to kneeling and climbing postures was quite similar and the overall agreement among the methods for assessing the leg postures was high. The most frequent misclassification involved the categorization of standing leg postures. The observers were more likely to misclassify flexed knee postures as neutral (straight knee) than neutral postures as flexed. A similar phenomenon was found for walking postures. The misclassification of standing postures may have been due to limitation on the observers' ability to estimate the degree of flexion in both legs simultaneously, with a bias towards coding the knees as straight, or it may have been caused by a systematic error in the reference measurements. The latter would be more likely if mildly flexed standing postures were frequent in the simulated tasks. A laboratory study demonstrated that when the knees were flexed 30 degrees, the electronic inclinometers recorded knee flexion ≥ 35 degrees 30% to 40% of the time (see Chapter II).

Agreement among the methods was lowest for the assessment of trunk postures. The assessment of the trunk-posture categories required simultaneous quantitative evaluation of the angles of the shoulders and hips in three planes. Additionally, the changes between trunk-posture categories occurred frequently and quickly during the dynamic activities for some tasks. The arm and leg-posture categories were broader and represented motion only in one plane, so these postures were easier to judge. The arm-posture categories changed much less frequently than the leg and trunk categories, perhaps also contributing to the ease assessing arm postures in these tasks.

Despite difficulties in evaluating trunk postures, overall agreement among the methods was moderately high. The frequency of neutral and flexed trunk postures was similar, although the frequency of these exposures were slightly over-estimated with the work-sampling methods. This over estimation, however, resulted because the frequency of trunk lateral bending or torsion, and frequency of flexion with trunk lateral bending or torsion, were under-estimated with the work sampling approaches. When the 5 trunk-posture categories were re-defined into 3 categories of trunk flexion (< 20 degrees, > 20 and ≤ 45 degrees, and ≥ 45 degrees), the frequency differences among the methods narrowed and the agreement among the methods for assessing trunk flexion increased dramatically. No significant differences (Chi Square on 4 d.o.f. = 0.674, p=0.955) were found in the frequency of trunk flexion categories and kappa coefficients exceeded 0.7 for all comparisons (Figure 29 and Table 29).

These results suggest that while the frequency of trunk-lateral bending or torsion tend to be underestimated with work sampling, categories of trunk flexion may be measured more accurately. This may be because trunk torsion, in particular, is difficult to visualize since it involves estimating the position of the shoulders relative to the hips in the transverse plane, while the observations are most likely made from a sagittal or coronal view. Heinsalmi (1986) also reported that observers had difficulty in differentiating between neutral and twisted trunk postures.

2. Differences Between Simplified PATH and PATH

Agreement with the reference measurements was consistently higher with simplified PATH than with PATH. While observers were assigned to perform either simplified PATH or PATH for the duration of the study, the results are probably less likely due to differences in expertise among observers and more likely due to the decreased cognitive demands placed on the simplified PATH observer. The experience of each observer was similar and previous research has demonstrated reasonably high inter-observer reliability for evaluating body postures with PATH (Buchholz et al., 1996). These findings support the hypothesis that the measurement of postures may improve when the observer is required to code fewer exposures. In this case, more than one observer would then be required to record the same amount of information at each observation. For example, one observer could code body postures while the other codes tasks and activities (van der Beek et al., 1992). However, the simultaneous characterization of postures and activities is more difficult to achieve with this type of approach because even small systematic differences in the time of observation between coders may affect the results. Another approach may be to limit the number of exposures in the assessment.

3. Limitations

The results of the study are, to some degree, limited by the characteristics of the observers who collected the observational data. The accuracy of the observations is very likely dependent on the expertise and experience of the observer. The results of this study probably reflect what could be expected of experienced observers. Both PATH and the simplified PATH observers had received 32 hours of PATH training and had used PATH in a variety of work settings intermittently for more than one year previous to this study.

The results of the study may be more favorable than those expected for a busy construction site in which there are many potential distractions (e.g., heavy equipment operation or traffic) or during extremely dynamic working conditions. The study was conducted in a semi-controlled environment, in which observers were familiar with the tasks and the environmental conditions were close to ideal. The six tasks could easily be distinguished from one another, and each task was performed without interruption. This is similar to the way work is performed on highway construction sites, where one task is often performed for several minutes or hours before changing to another task. Finally, the weather conditions during the study were temperate, and observers made observations from approximately 10 m from the subjects.

While these conditions represent close to the ideal conditions for observers on actual construction sites, many efforts were made to create an environment that was as close as possible to an actual construction site. Data were collected outside on a mock-construction site equipped with a trench, truck, and construction materials, and the tasks were designed to be similar to those typically observed on construction sites. Subjects were also clothed in apparel similar to that worn by construction workers during the climatic conditions of the study. Observers were blinded to the exact task that was performed until the beginning of the data collection period.

Observations were made only on 1 subject during each observation period. This was necessary because reference measurements could be made on only one subject at a time. While making repeated measurements on 1 worker may be logistically easier than making observations on a group of workers in random order (as is typically done with PATH), it is not expected that the latter would result in large decreases in measurement accuracy. The cognitive demands of locating a worker occur before and separately from those of the actual observation. In this study, no attempt was made to determine the effects of distance between observers and workers or weather conditions on the validity of the observational methods.

The posture categories of the work-sampling methods evaluated in this study are relatively crude. As the number of categories increases or the categories become more precise (narrow), the probability of random misclassification among observers will most likely increase and the inter-method reliability will decrease. If the misclassification of exposure categories is truly random, however, the overall characterization of body posture frequency may closely approximate the true exposure.

The reliability of the work-sampling methods may be affected by the frequency of observation, characteristics of the subjects observed and the type of work performed; all of which were limited in this study. The sampling interval for the PATH measurements for each observer was fixed at 60 seconds and the sampling interval for simplified PATH was 30 seconds. The time interval for the PATH measurements was chosen because it was consistent with what observers often choose when first collecting data on construction sites. The time interval for the simplified-PATH measurements was chosen simply to correspond with the PATH observations. Other researchers have used 15 or 20 second intervals for methods similar to simplified PATH (Burdorf et al., 1992; Mattila et al., 1993; van der Beek et al., 1992). The amount of active or dynamic work has been suggested to affect the reliability of observations for postural assessment (Burdorf, 1992; Leskinen, et al., 1997). In this study, there were an inadequate number of observations made on the individual workers performing individual tasks to evaluate the effects of worker and task characteristics on the reliability of the measurements. Most of the tasks in this study tended to be dynamic in nature, requiring the subject to change postures frequently.

While it is common to assess agreement among measurement methods with statistics such as proportion of agreement and kappa coefficients, these evaluations are limited because the measured strength of agreement depends on the prevalence of the exposure categories (Feinstein and Cicchetti, 1990). This becomes a significant problem when chance agreement between methods is large, resulting in a high proportion of agreement and a low kappa coefficient. This problem was avoided by designing tasks that facilitated a variety of working postures to minimize the role of chance agreement. This is indicative of the results, for which the proportion of agreement and kappa coefficients were consistently similar.

There are several limitations involving the reference system which should be mentioned. First, the electronic postural measurement system was found to be reasonably accurate in a laboratory study of static postures but was not tested under dynamic conditions. The electronic inclinometers were sensitive to body accelerations, and it is possible that their accuracy may have been compromised during some of the dynamic work activities, such as sweeping or shoveling. However, review of the video tape after the electronic inclinometer data were analyzed did not show this to be true. For example, the electronic inclinometers recorded shoulder flexion below the shoulders during sweeping activities, despite the constant motion of the upper arms during this work. Additionally, the electronic inclinometer measurements of knee flexion were used only during standing postures and were disregarded during other leg posture conditions such as walking. An attempt was also made to increase the stability of the electronic inclinometer measurements at each observation by increasing the sampling frequency of the inclinometers by taking the average of measurements made 0.25 seconds before and 0.25 seconds after the moment of observation. Measurements of trunk lateral bending or torsion were less likely to be compromised due to body motion, as the LMM is designed to measure lumbar postures in dynamic work situations (Marras et al., 1992, 1993, 1995).

E. CONCLUSIONS

In this study, both work-sampling based methodologies provided measurements of arm, leg and trunk postures that closely approximated reference measurements. The highest agreement was found in the classification of shoulder postures. Discrepancies among the reference and work-sampling methods were found in the identification of knee flexion and trunk lateral bending and torsion. The results of this study are representative of construction work performed under close to ideal observational conditions. The effects of sampling frequency, subject characteristics, observer experience and nature of the tasks still need to be evaluated.

F. RECOMMENDATIONS

1. Work-sampling based approaches are recommended in the assessment of exposure frequencies for arm postures at or above shoulder height, trunk flexion, kneeling and climbing during construction work.
2. When only some of the PATH variables are of interest in a study, it is recommended that the extraneous variables be dropped to possibly improve the accuracy of the assessments.
3. Direct-postural methods should be used in the evaluation of knee flexion, trunk lateral bending and trunk torsion in construction work when possible. When such methods are not feasible, a simplified version of PATH (e.g., an observer codes only these specific postures) may help improve the accuracy of the observations. Further research should be performed to test this hypothesis.
4. Further research should be aimed at the evaluation of work-sampling based approaches under different experimental conditions (e.g., dynamic and sedentary work, and good and poor observational conditions) to provide more information on the situations in which discrete interval observations provide valid assessments of working postures.

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TABLE 16

Reference measurements of posture for the simulated construction tasks

Exposure	Discrete Interval Measurements	Continuous Measurements
Shoulder Posture	The mean electronic inclinometer (EI) measurements collected at 50 Hz over a period of 0.5 seconds before and after the work-sampling observation.	EI measurements collected at 2 Hz throughout the entire task.
Leg Posture	Frozen frame video analysis at the instant of work-sampling observation to identify standing, walking, kneeling, squatting and climbing. For standing postures, mean IE measurements (difference between voltages for upper and lower legs) used to identify knee flexion ≥35 degrees. Measurements collected at 50 Hz over a period of 0.5 seconds before and after the work-sampling observation.	Simulated real-time analysis to identify standing, walking, kneeling, squatting and climbing. For standing postures, EI measurements (difference between voltages for upper and lower legs) used to identify knee flexion ≥35 degrees. EI measurements collected at 2 Hz.
Trunk Flexion	EI data collected at 50 Hz over a period of 0.5 seconds before and after the work-sampling observation.	EI data collected at 2 Hz throughout the entire task.
Trunk Lateral Bending and Torsion	LMM measurements collected at 60 Hz over a period of 0.5 seconds before and after the work-sampling observation.	LMM measurements collected at 60 Hz over a period of 5 seconds before and after the work-sampling observation (1/3 of the task).

note: IE: electronic inclinometer, LMM: Lumbar Motion Monitor

TABLE 17

Inter-method reliability (proportion agreement and kappa coefficient) for shoulder posture categories during simulated construction tasks

Methods	Proportion Agreement	Kappa (*k*)
Inclinometers and Simplified PATH (n=461)	0.95	0.80
Inclinometers and PATH (n=457)	0.93	0.74
Simplified PATH and PATH (n=455)	0.93	0.75

TABLE 18

Categories of shoulder posture compared between the reference and simplified PATH methods (n=461). The diagonal from the upper left to lower right represents the number of observations for which there was agreement

		Simplified PATH: Arms below Shoulders	Simplified PATH: 1 Arm above Shoulders	Simplified PATH: Arms above Shoulders	Total
Electronic Inclinometers	Arms below Shoulders	**388**	15	0	403
Electronic Inclinometers	1 Arm above Shoulders	2	**16**	2	20
Electronic Inclinometers	Arms above Shoulders	2	0	**36**	38
	Total	392	21	38	**461**

TABLE 19

Categories of shoulder posture compared between the reference and PATH methods (n=457). The diagonal from the upper left to lower right represents the number of observations for which there was agreement

		PATH			
		Arms below Shoulders	1 Arm above Shoulders	Arms above Shoulders	Total
Electronic Inclinometers	Arms below Shoulders	**384**	12	3	399
	1 Arm above Shoulders	4	**12**	4	20
	Arms above Shoulders	1	1	**36**	38
	Total	389	25	43	**457**

TABLE 20

Time-weighted exposure frequency measured with the reference method and observation-weighted exposure frequency measured with work-sampling methods for the arm-posture categories

Posture	Reference	Simplified PATH			PATH		
	(TWE) 13488 seconds	(OWE) 461 obs.	Lower 95% CI	Upper 95% CI	(OWE) 457 obs.	Lower 95% CI	Upper 95% CI
Arms Neutral	0.86	0.85	0.82	0.88	0.85	0.82	0.88
1 Arm above Shoulders	0.07	0.07	0.04	0.09	0.05	0.03	0.08
Arms above Shoulders	0.08	0.08	0.06	0.11	0.09	0.07	0.12

TABLE 21

Inter-method reliability (proportion agreement and kappa coefficient) for leg postures during simulated construction tasks

Methods	Proportion Agreement	Kappa (k)
Inclinometers/Video and Simplified PATH (n=462)	0.90	0.87
Inclinometers/Video and PATH (n=459)	0.81	0.75
Simplified PATH and PATH (n=458)	0.84	0.76

TABLE 22

Categories of leg posture compared between the reference and simplified PATH methods (n=461). The diagonal from the upper left to lower right represents the number of observations for which there was agreement

		Simplified PATH						
		Neutral	1 leg in Air	Knees Flexed	Walk	Kneel	Climb	Total
	Neutral*	**91**	0	2	1	0	0	94
Video	1 leg in Air+	0	**5**	0	0	0	0	5
and	Knees Flexed*	16	3	**69**	1	0	1	90
Electronic	Walk+	10	5	2	**126**	0	2	145
Inclinometers	Kneel+	0	0	0	0	**103**	0	103
	Climb+	1	1	1	0	0	**21**	38
	Total	118	14	75	128	103	24	**461**

+ determined from video tape with frozen-frame analysis
* measured with inclinometers for standing postures identified with video tape

TABLE 23

Categories of leg posture compared between the reference and PATH methods (n=461). The diagonal from the upper left to lower right represents the number of observations for which there was agreement

		PATH						
		Neutral	1 leg in Air	Knees Flexed	Walk	Kneel	Climb	Total
	Neutral	**85**	0	6	4	0	0	95
Video	1 leg in Air	1	**3**	1	0	0	0	5
and	Knees Flexed	36	1	**50**	1	0	0	88
Electronic	Walk	19	2	6	**115**	1	0	143
Inclinometers	Kneel	0	0	0	0	**103**	0	103
	Climb	1	0	1	2	0	**20**	24
	Total	118	14	75	128	103	24	**458**

+ determined from video tape with frozen-frame analysis
* measured with inclinometers for standing postures identified with video tape

TABLE 24

Time-weighted exposure frequency for the leg-posture categories measured with the simulated real-time video analysis methods and electronic inclinometers and observation-weighted exposure frequency measured with work-sampling methods

Posture	Video and Electronic Inclin. (TWE) 13488 seconds	Simplified PATH (OWE) 462 obs.	Simplified PATH Lower 95% CI	Simplified PATH Upper 95% CI	PATH (OWE) 459 obs.	PATH Lower 95% CI	PATH Upper 95% CI
Walking+	0.32	0.28	0.24	0.32	0.27	0.23	0.31
Knee Flexion*	0.26	0.17	0.14	0.20	0.14	0.11	0.17
Climbing+	0.04	0.05	0.03	0.07	0.04	0.02	0.06
Legs Straight*	0.19	0.25	0.21	0.29	0.31	0.27	0.35
Kneeling+	0.22	0.22	0.19	0.26	0.22	0.19	0.26

+ determined from video tape with frozen-frame analysis
* measured with inclinometers for standing postures identified with video tap

TABLE 25

Inter-method reliability (proportion agreement and kappa coefficient) for trunk postures during simulated construction tasks

Methods	Proportion Agreement	Kappa (*k*)
Inclinometer/LMM and Simplified PATH (n=463)	0.74	0.60
Inclinometer/LMM and PATH (n=456)	0.68	0.51
Simplified PATH and PATH (n=456)	0.75	0.58

TABLE 26

Categories of trunk posture compared between the reference and simplified PATH methods (n=463). The diagonal from the upper left to lower right represents the number of observations for which there was agreement

		Simplified PATH					
		Neutral	Mild Flexion	Severe Flexion	Lateral Bend or Twist	Flexion and Bend or Twist	Total
	Neutral	**219**	12	1	3	1	236
Electronic Inclinometers	Mild Flexion	9	**30**	5	2	3	49
	Severe Flexion	3	5	**58**	0	6	72
	Lateral Bend or Twist	30	6	1	**4**	1	42
	Flexion and Bend or Twist	3	3	24	1	**33**	64
	Total	264	56	89	10	44	**463**

TABLE 27

Categories of trunk posture compared between the reference and PATH methods (n=456). The diagonal from the upper left to lower right represents the number of observations for which there was agreement

		PATH: Neutral	Mild Flexion	Severe Flexion	Lateral Bend or Twist	Flexion and Bend or Twist	Total
Electronic Inclinometers	Neutral	**211**	11	3	6	1	232
	Mild Flexion	14	**24**	7	2	2	49
	Severe Flexion	7	5	**51**	2	5	70
	Lateral Bend or Twist	28	6	1	**6**	0	41
	Flexion and Bend or Twist	2	10	24	5	**23**	64
	Total	262	56	86	21	31	**456**

TABLE 28

Time-weighted exposure frequency measured with the reference method and observation-weighted exposure frequency measured with work-sampling methods for the trunk-posture categories

Posture	Reference (TWE) 13488 seconds	Simplified PATH (OWE) 463 obs.	Simplified PATH Lower 95% CI	Simplified PATH Upper 95% CI	PATH (OWE) 458 obs.	PATH Lower 95% CI	PATH Upper 95% CI
Neutral	0.62	0.58	0.54	0.63	0.60	0.56	0.65
Mild Flexion	0.17	0.16	0.13	0.19	0.16	0.13	0.19
Severe Flexion	0.21	0.26	0.22	0.30	0.23	0.19	0.26
Lateral Bending	0.13	0.06	0.04	0.08	0.06	0.04	0.08
Torsion	0.13	0.06	0.04	0.08	0.06	0.04	0.08

note: Posture categories were reorganized so that flexion, lateral bending and torsion could be analyzed separately (i.e., combinations of postures not considered).

TABLE 29

Inter-method reliability (proportion agreement and kappa coefficient) for categories of trunk flexion during simulated construction tasks

Methods	Proportion Agreement	Kappa (*k*)
Inclinometer and Simplified PATH (n=463)	0.86	0.75
Inclinometer and PATH (n=456)	0.85	0.73
Simplified PATH and PATH (n=456)	0.85	0.73

a)

b)

Figure 20. Simulated construction tasks performed by the subjects: a) move crushed rock, b) move lagging/wood beams, c) apply roof cement to blocks, d) remove dirt from black-top, e) drill holes in concrete, and f) move bricks/blocks

c)

d)

Figure 20 cont.

e)

f)

Figure 20 cont.

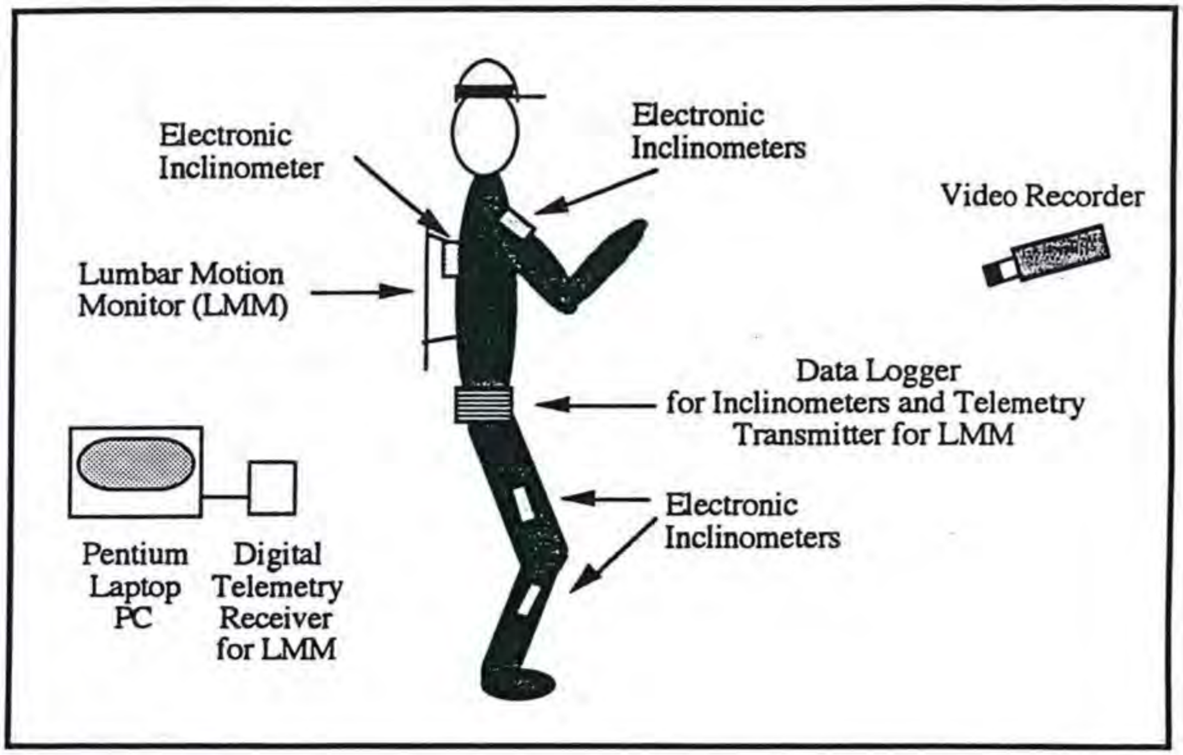
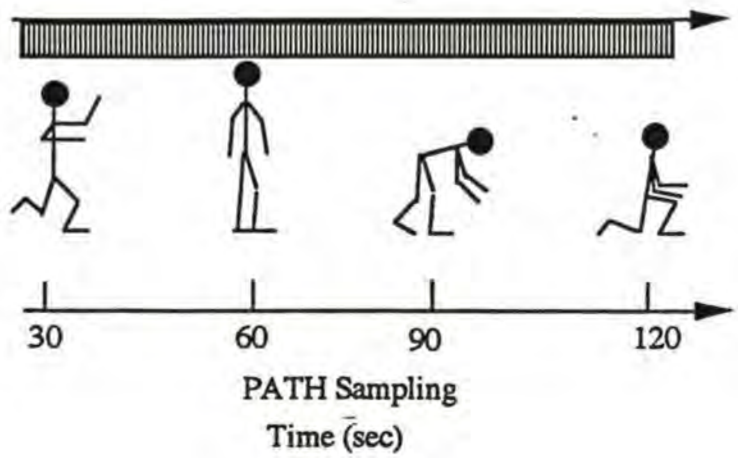


Figure 21. Schematic of the reference system used in the evaluation of work sampling for postural assessment during simulated construction tasks.

Figure 22. The electronic inclinometers are fitted to the knees of the subject.

Figure 23. Calibration of the LMM for trunk lateral bending. The worker is shown with the trunk laterally bent 20 degrees to the right as measured with a weighted inclinometer.

a) video recording of standing, walking, squatting and kneeling postures and inclinometer recording of arm posture, knee flexion and trunk flexion



b) LMM recording of trunk lateral bending and torsion

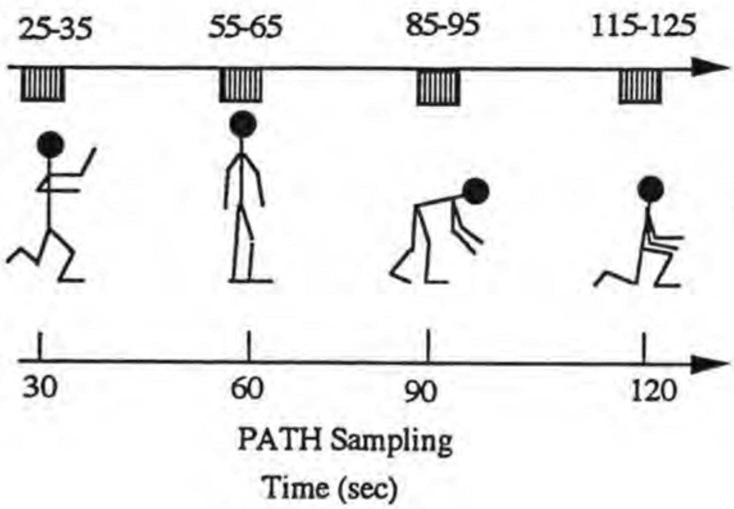


Figure 24. Sampling approaches used for the electronic inclinometers, LMM and video analysis.

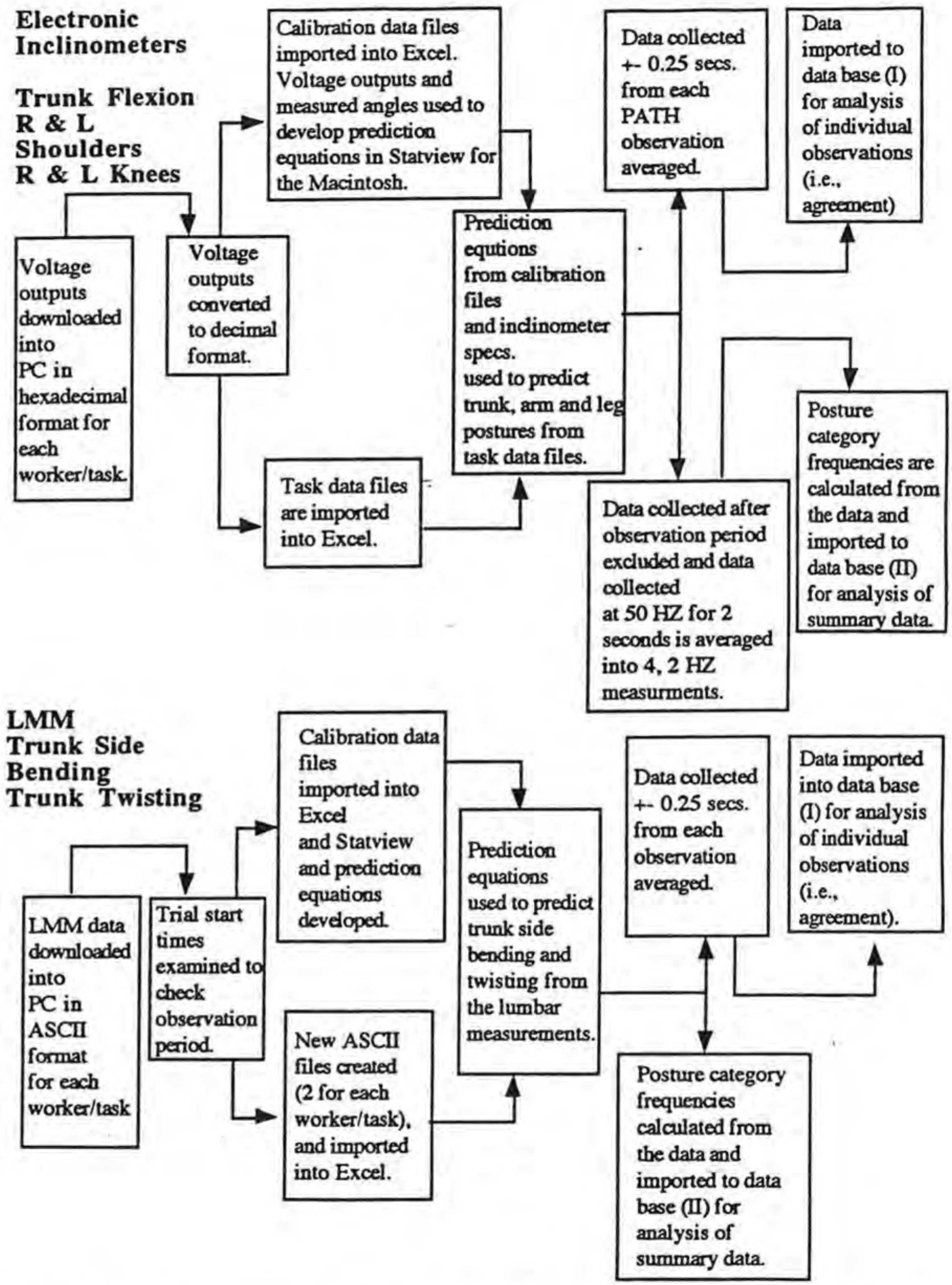
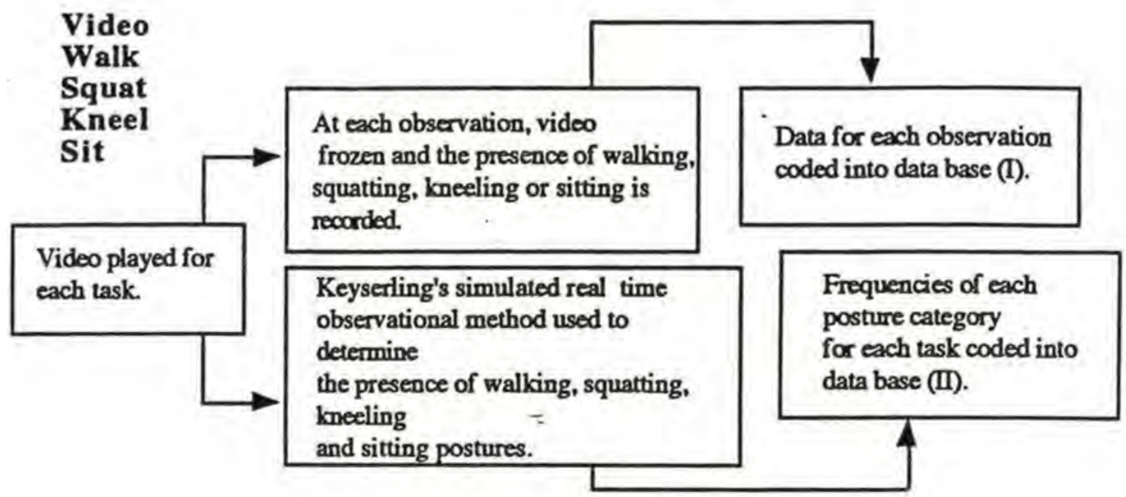


Figure 25. Data management procedures for the reference and observational work sampling postural assessment methods.



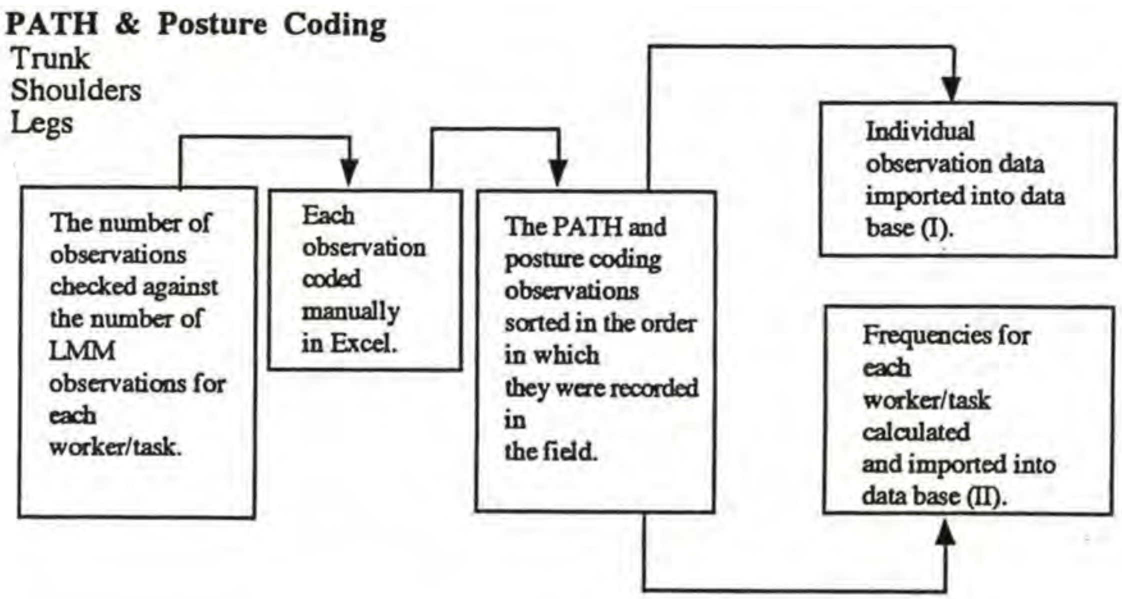


Figure 25 cont.

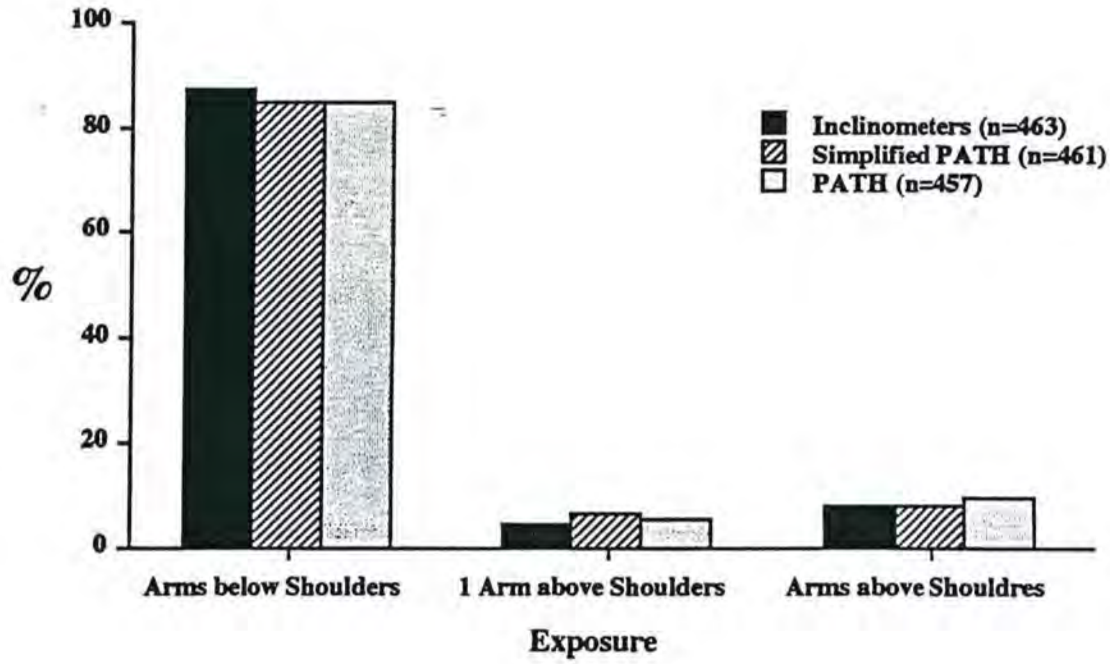


Figure 26. Frequency of arm-posture categories for each of the measurement methods.

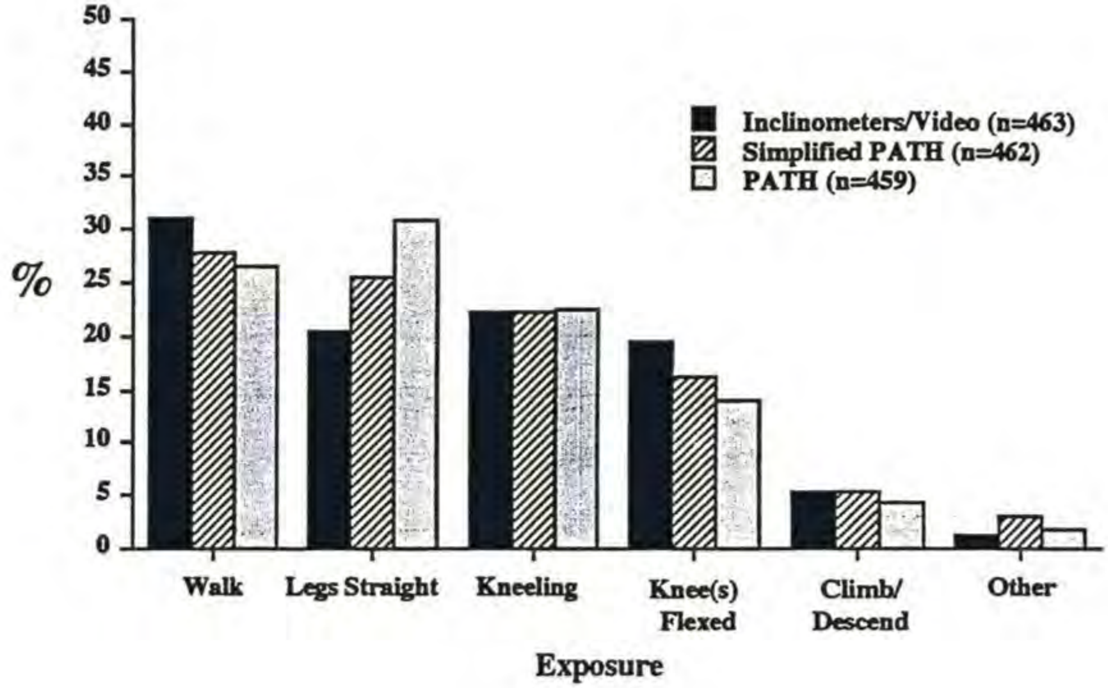


Figure 27. Frequency of leg-posture categories for each of the measurement methods.

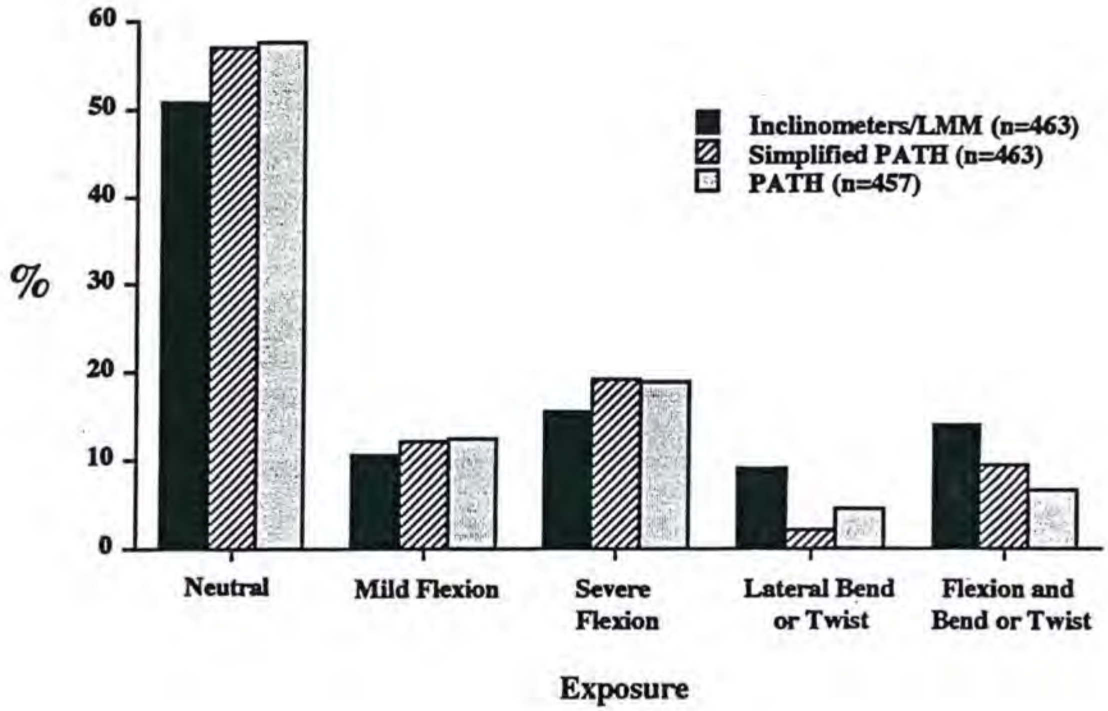


Figure 28. Frequency of trunk-posture categories for each of the measurement methods.

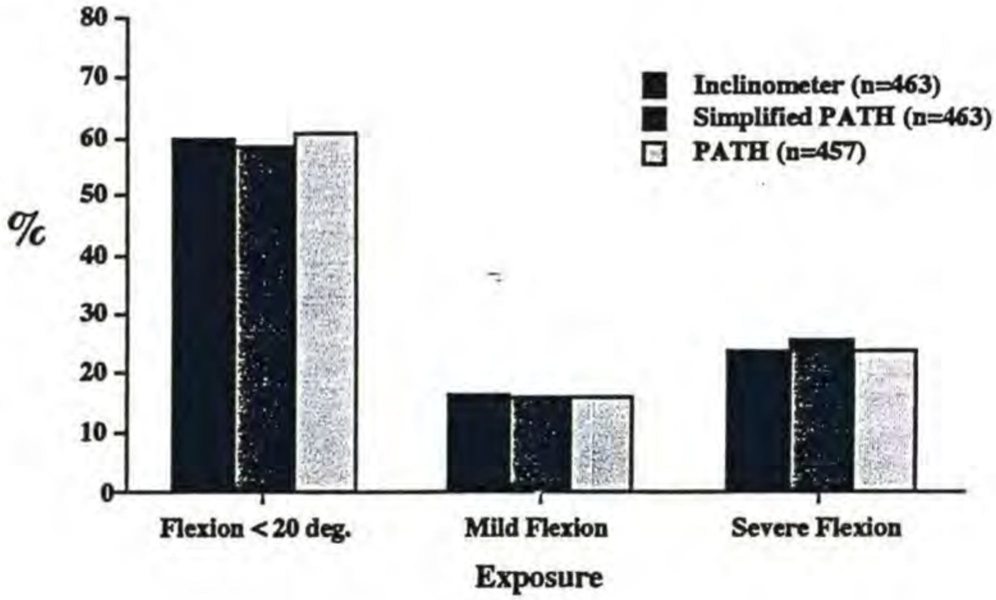


Figure 29. Frequency of trunk flexion for each of the measurement methods.

CHAPTER IV. AN EVALUATION OF ERGONOMIC EXPOSURES DURING HIGHWAY CONSTRUCTION WORK FOR THE DEVELOPMENT OF RELIABLE EXPOSURE ASSESSMENT STRATEGIES

A. INTRODUCTION

Direct measurement methods and discrete interval observations of posture were evaluated in the previous two chapters. The electronic inclinometers and goniometers were evaluated with manual postural measurement devices and were shown to predict static trunk, arm and leg postures accurately on continuous and categorical scales (Chapter II). Categories of body posture estimated with PATH and a simplified version of PATH generally agreed highly with measurements recorded with the electronic postural assessment system during simulated construction work (Chapter III). Assuming that measurements could be made on all workers in a study group for a representative set of working conditions, one could then be reasonably confident in the accuracy of exposure measures with either the continuous direct-measurement or observational work-sampling methods.

However, the use of these methods under such circumstances is often not logistically or economically feasible. Often measurements must be made on a sample of workers over a limited amount of time. With such an approach, groups of workers of the same occupation or who perform the same job tasks are defined and assumed to have similar exposures; measurements are then made for a subset of workers in each homogeneous exposure group (Boleij et al., 1995). When the assessments are not made on a representative sample of the working population and working conditions, or when "homogenous exposure groups" do not, in fact, have similar exposures, a biased exposure estimate for the group is likely.

Although job title or occupation 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, there may be great variation in these exposures among workers within the same occupation and among different days, as well as within a given day, for individual workers. Using occupation as a surrogate for exposure when there is a large variability in exposure within occupations can lead to exposure misclassification and bias the risk assessment of the exposure when occupations are compared to one another. Additionally, when a relationship between occupation and health outcome is found or when an increase in an ergonomic-related health outcome is identified for an occupation, the information necessary for the development of the appropriate controls may not be available. The importance of measuring ergonomic exposures with enough precision to aid in the development of effective controls has been expressed by others (Hagberg, 1992; Winkel and Mathiassen, 1994).

Exposures may vary both among workers and among days for individual workers within an occupation because a wide variety of work tasks are required of an occupational group and the distribution, duration and content of the work tasks may vary among individuals and days. One way to improve the quality of the exposure information and provide information to aid the development of controls under these circumstances is to estimate the task distribution for each job and measure the ergonomic exposures for tasks (Winkel and Mathiassen, 1994). Unfortunately, long measurement periods may be required to acquire reliable measures of the task distribution and task exposures in 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 this type of work.

Several observational work sampling approaches designed to measure ergonomic exposures in work have been described in detail (e.g., Karhu et al., 1977; van der Beek et al., 1992; Buchholz et al., 1996). For these evaluations, observations are made on a sample of workers over a period of time that is considered representative of the population and work performed. While these methods have been used extensively by ergonomics researchers 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 in a given occupation.

Obtaining reliable measures of group exposure requires knowledge about how exposures vary over time and among workers within each group. The amount of time needed for a reliable assessment of long-term exposure increases with the variability of exposure over time (e.g., within-day or day-to-day variability). Ideally, workers within a group have the same long-term exposure level, and, thus, the exposures for a relatively small sample of workers will reflect that of the entire group. The number of workers needed for a reliable exposure estimate, however, increases as the exposure variability among workers increases. If the variability of exposure among workers within groups is so high that there is a large overlap of exposure between groups, the grouping strategy may not be suitable for the evaluation of the exposure.

What is known about how ergonomic exposures are distributed among workers and over time has been limited to the study of postural load on the back for relatively few occupations (Burdorf et al., 1994; van der Beek et al., 1995; Burdorf, 1995; Burdorf and van Riel, 1996). Furthermore, only one of these studies has specifically addressed the exposure assessment strategies that are required to provide reliable estimates of exposure for groups of workers (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. Therefore, a realistic assumption about construction work is that the variability among workers within a trade and among days for individual workers is extremely high. These sources of exposure variance need to be considered for the reliable assessment of exposures in construction work.

As part of an ongoing research project, an observational work-sampling approach, PATH, has been developed to evaluate the ergonomic demands on workers during highway construction work (see Chapter I). With PATH, the assessment are made to provide exposure information for tasks performed by each trade to limit the within-group exposure variability resulting from differences in the distribution of tasks among workers. Because of potentially large exposure variability among workers even within tasks, an observational work-sampling approach was chosen over more detailed methods of assessment so that measurements could be obtained on multiple workers over long time periods.

One of the underlying assumptions of the task-based approach to exposure assessment is that exposures depend on the job tasks performed. While anecdotal evidence in the observation of construction work supports the assumption that ergonomic exposures vary among construction tasks within a trade, this hypothesis has yet to be scientifically tested for different ergonomic exposures during different types of construction tasks.

When exposures vary among tasks, the assessment should be aimed at obtaining reliable task-specific estimates of ergonomic exposures. For this, information about the between-worker and within-worker variability of exposures within task is needed. Sampling strategies that accommodate the exposure variability can then be developed to provide reliable estimates of exposure by informing decisions as to the number of workers and days needed.

The objective of this research was to provide guidelines for the reliable assessment of ergonomic exposures in construction work. For this, the efficacy of using a task-based observational work-sampling approach for the assessment of exposures was examined with an analysis of exposure variability among tasks. The between-worker and within-worker components of exposure variability within tasks were also evaluated. Finally, the reliability of different assessment periods was evaluated for several exposures using bootstrap analysis.

B. METHODS

1. 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 endeavor (12 years anticipated at present). 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 shaft and carpenters building and erecting forms. Data were collected separately for each trade.

Iron workers 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 parts (1 for each direction of traffic) and outside walls. Preparation work included moving materials, guiding crane loads, erecting scaffolding along rebar walls and clearing debris. Two tasks observed (caisson construction and supervision) were excluded from the analyses due to sparse data.

Laborers 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 digging 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 watching the members of the crew who were in the pit. Pit-wall construction consisted of 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 jack hammer and shoveling 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 iron 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. 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 check-list type format. Unlike most observational methods that use checklists, evaluations 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 3 operations. 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 intervals, usually 45 or 60 seconds. 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 for PATH codes.

The evaluation of the 3 concrete-reinforcement job tasks included a total of 1790 observations, with 15 to 17 workers observed performing each task on 10 to 13 days. The assessment of the 4 laborers' job tasks in jacking-pit construction included 3219 observations, with 7 to 10 workers observed and 9 to 13 days of observation for each task. Eight hundred forty-three observations were made on the carpenters' tasks, in which 4 to 8 workers were observed for each task on 6 to 8 days. Each worker was not observed performing all of an operation's tasks (Table 30).

3. Exposure Variables

Nine exposure variables were examined for each of the 10 tasks included in the analyses. The exposure variables were:

- 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.

While the definitions of body postures and tool use categories were consistent among the operations (see Buchholz et al., 1996 for definitions), the characterization of MMH and load handling differed slightly. For the iron workers and laborers, the loads handled were estimated and coded to the nearest 5 N and were then grouped into 6 categories (0 N, 0 N $<$load$<$ 10 N, 10 N $\leq$ load $<$ 44 N, 44 N $\leq$ load $<$ 132 N, 132 N $\leq$ load $<$ 223 N, load $\geq$ 223 N). MMH activities were defined as those that involved handling at least 44 N, excluding activities that involved hand tool or power tool operation (e.g., carrying a jack hammer from one location to another was defined as MMH but operating a jack hammer was not). Load handling involved at least 44 N but included the use of tools and equipment that were at least 44 N. For the carpenters, data were collected with an older version of PATH in which loads were coded directly into 5 categories (0 N, 0 N $<$ load $<$ 23 N, 23 N $\leq$ load $<$ 67 N, 67 N $\leq$ load$<$ 223 N, load $\geq$ 223 N). MMH and load handling involved handling at least 67 N during the carpentry tasks.

4. 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.

Fifty-five daily-exposure estimates were obtained on a total of 10 iron workers during concrete reinforcement work. There were 20 daily exposure estimates on a total of 6 different workers during ground-level rebar construction, 20 exposure estimates on a total 7 workers during wall-rebar construction and 15 exposure estimates on 5 different workers during preparation work. The number of daily exposure estimates and workers for load handling, hand-tool use and power-tool use during wall rebar construction and for hand-tool use and power-tool use during preparation work was slightly lower due to missing data (i.e., for these exposure-task combinations, missing observational data reduced the number of observations for an individual to less than 10). The mean number of observations used to calculate an individual's daily exposure ranged from 17 to 22 (Table 31).

Thirty-three estimates of daily exposure were available for a total of 7 laborers during jack-pit construction. There were 4 daily-exposure estimates for 2 different workers during top work, 9 daily estimates for 4 workers during pit-wall construction, 11 daily estimates for 4 workers during manual excavation and 9 daily estimates for 4 workers during miscellaneous work. The number of daily-exposure estimates and workers for exposures to arms above shoulder height and power-tool use during pit-wall construction, power-tool use and MMH during manual excavation and laterally bent or twisted trunk postures, hand-tool use and power-tool use during miscellaneous work was slightly lower due to missing data. While the number of workers for each task was lower in this operation than in the concrete reinforcement work, the mean number of observations used to calculate an individual's daily exposure was much higher, ranging from 30 to 107 (Table 32).

There were 27 daily estimates of exposure on a total of 9 carpenters during 3 form construction tasks. For form building, there were 9 daily estimates of exposure for 3 different workers in a shop and 7 daily estimates of exposure for 3 workers on site. Eleven daily estimates of exposure were available for 4 workers during form erection. The number of daily-exposure estimates and workers for exposures to load handling in all tasks, arms at or above shoulder height during form building in a shop, kneeling, squatting or bent leg postures, hand-tool use or power-tool use during form building on site, and power-tool use during form erection was less due to missing data. The mean number of observations used to calculate an individual's daily exposure ranged from 22 to 33 (Table 33).

5. Data Analysis

Exposure Variability due to Task within Operation

The first data analysis was designed to evaluate ergonomic exposure frequencies among the tasks of 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 exposure was predicted with the mixed-effects model:

$$y_{ijk} = \mu + T_i + W_j + e_{ijk} \quad (4.1)$$

where,

y_{ijk}= the predicted exposure for task level i, worker level j and measurement k

μ = the grand mean

T_i = the effect of task i (fixed effect)

W_j = the effect of worker j (random effect)

e_{ijk} = the random error of the kth measurement on the jth worker in the ith task

i = task number

j = worker number

k = measurement number

For this model, the levels of the fixed effect represent the population of levels under study (i.e., the tasks of an operation) and those of the covariance parameter (random effect) are thought to be drawn randomly from an infinite population of levels (i.e., a sample of workers drawn from a population of workers). Because random effects are variables in 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). For this model, as with the mixed-effects model described above, 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.

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

The second analysis was designed to examine the between-worker and within-worker components of exposure variability within task. For each task, the components of variance were calculated with a random effects ANOVA treating worker as a random effect. The exposure was predicted with the random-effect model:

$$y_{jk} = \mu + W_j + e_{jk} \quad (4.2)$$

where,

y_{ij} = the predicted exposure for worker level j in a specific construction task

μ = mean exposure among all workers for the task

W_j = the effect of worker j (random effect)

e_{jk} = the random error of the jth measurement on the ith worker

j = worker number

k = measurement number

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 may also be 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 (e.g., those which use sums of squares) for estimating the components of variance in crossed-unbalanced designs (Lindman, 1974).

Bootstrapping to Evaluate the Number of Days Needed for Reliable Exposure Assessment

Bootstrapping is a statistical approach which allows inferences to be made without strong assumptions about a sample's population distribution. Instead, the major assumption of the bootstrap 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. This is similar to Monte Carlo sampling in which the population distribution is sampled repeatedly to estimate the distribution of a statistic.

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 'resamples'. The resampling of the empirical probability distribution and statistic calculation is then repeated many times. A probability distribution of the statistic is then constructed from the resamples by placing a probability of 1/x (where x is the number of resamples) 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 1,000 resamples are recommended (see Mooney and Duval, 1993 for a detailed description of bootstrapping).

The third analysis procedure employed bootstrapping to evaluate the reliability of exposure estimates for groups of workers performing the same task. The primary aim of the analysis was to determine the least number of observation days (each day having at least 40 observations) needed to characterize reliably exposures of different frequencies and between-day variances for groups of workers. The frequency of exposure was hypothesized to have an effect on the appropriate sampling strategy in this case, because the reliability of measurements obtained with work sampling is a function of the exposure frequency and number of observations made (Pape, 1992).

The mean daily exposure was calculated for each exposure-task combination 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 (not from the average of all workers' daily exposures). 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, improving the precision of the measurement in a group's daily exposure.

Mean daily estimates of group exposure were bootstrapped to determine the number of days necessary for a reliable task-specific estimate of mean group exposure. For each selected task-exposure combination, daily group estimates of exposure were calculated. The distribution of exposure frequencies for each sample was used to estimate the true exposure distribution for the task with the bootstrap.

The bootstrap procedure was used to simulate the obtained daily-group estimates of exposure for assessment periods of 1 day up to the total number of days in each data set, using Stata software (Stata Corporation, 1997). For each simulated observation period, 1000 resamples (sets) were drawn with replacement from the empirical distribution of the original sample. Each set had the same number of values as days in the observation period and the mean value (mean-daily exposure) was calculated for each set. The mean exposure and 95th percentile confidence limits of the 1000 sets were then recorded for each assessment period. The confidence limits were simply the 25th lowest and 25th highest values of mean exposure for the 1000 sets. The percentile method for determining the confidence limits seems to be the best of several methods for estimating confidence limits when the true distribution of exposure is unknown (Mooney and Duval, 1993).

The mean and 95th percentile confidence limits were plotted against the different assessment periods for each exposure. Differences in the confidence intervals among observation periods, for exposures with similar frequencies but different degrees of variability and differences in mean exposure frequencies, were evaluated qualitatively but not statistically tested.

The bootstrap analysis was originally performed on 6 variables for each operation. From these 18 evaluations, 4 were chosen to represent different levels of exposure frequency (high and low) and variability (high and low) during the first 2-days of assessment. Two-day exposure frequencies that exceeded 25% were considered high and those below 8% were considered low. The 2-day exposure variability was considered high when the standard deviation > 5 and low when the standard deviation was < 2. The cut-off points for high and low exposure frequency and variability were somewhat arbitrary, but permitted at least 1 exposure-task combination in the operations examined to fall within each of the categories. The goal of using the first 2 days of assessment to estimate exposure frequency and variability was to develop a sampling strategy in which a decision for further data collection could be made after 2 days of initial data collection.

C. RESULTS

1. Exposure Variability due to Task within Operation

Ironworkers Reinforcing Concrete

There were often large differences in exposure frequency among the concrete-reinforcement tasks. These were statistically significant for 6 of the 9 ergonomic variables tested (Table 31). The frequency of any non-neutral trunk posture ranged from 32.3% to 52.0%, with significant differences among tasks ($F_{2,43}$=8.23, p>F=0.0009). The frequency of trunk flexion, ranging from 24.9% to 41.0%, also differed significantly among tasks ($F_{2,43}$=6.80, p>F=0.0027). The exposure frequency for kneeling, squatting or leg bending ranged from 12.6% to 34.8% for tasks ($F_{2,43}$=6.80, p>F=0.0027), hand-tool use ranged from 3.2% to 5.6% ($F_{2,43}$=6.80, p>F=0.0027), power tools use ranged from 0.5% to 9.7% ($F_{2,43}$=6.80, p>F=0.0027), and MMH ranged from 12.1% to 28.7% ($F_{2,43}$=6.80, p>F=0.0027). No significant differences among tasks were found in the frequency of trunk lateral bending or torsion (range from 20.3% to 28.2%), load handling ≥ 44 N (14.2% to 19.2%), and arm postures at or above shoulder height (6.2% to 8.9%).

Laborers Constructing a Jacking Pit for Utilities Relocation

There were also large differences in exposure frequency for a majority of the variables examined among the four laborers' tasks in the construction of a jacking pit (Table 32). Significant differences in exposure frequency among the tasks were found for 6 of the 9 variables, 5 of which were statistically significant in the analysis of the concrete reinforcement tasks. The frequency exposure among the tasks for any non-neutral trunk posture ranged from 17.5%-38.3% ($F_{3,24}$=5.55, p>F=0.0049), trunk flexion range from 13.5% to 47.5% ($F_{2,24}$=6.80, p>F=0.0026), kneeling, squatting or leg bending ranged from 20.7% to 46.5% ($F_{3,24}$=4.04, p>F=0.0178), load handling ranged from 6.7% to 47.9% ($F_{3,24}$=9.79, p>F=0.0002), hand-tool use ranged from 1.0% to 36.7% ($F_{3,23}$=7.68, p>F=0.0010), and MMH ranged from 0.8%-7.1% ($F_{2,21}$=3.39, p>F=0.0370). No significant differences were found in the frequency of trunk lateral bending or torsion (2.6% to 16.2%), arms at or above shoulder height (3.5% to 9.4%) and power-tool use (0% to 15.9%).

Carpenters Constructing Forms

Large differences were also found in the frequency of exposure among the 3 carpentry tasks in form construction (Table 33). There were significant differences in exposure for 4 of the 9 variables, of which 2 did not differ significantly among the concrete-reinforcement or jacking-pit construction tasks. The frequency of non-neutral trunk postures ranged from 33.8% to 61.0% ($F_{2,17}$=7.88, p>F=0.0038), trunk lateral bending or torsion ranged from 18.7%-44.5% ($F_{2,17}$=17.03, p>F=0.0001), arms at or above shoulder height ranged from 4.2%-11.4% ($F_{2,16}$=3.85, p>F=0.0430) and power-tool use ranged from 0%-11.6% ($F_{2,14}$=12.82, p>F=0.0007). No significant differences were found in the frequency of trunk flexion (25.7%-34.3%), in kneeling, squatting or leg bending (15.5% to 25.5%), load handling > 67 N (4.6% to 15.8%), hand-tool use (8.1% to 12.2%) and MMH (12.8% to 19.7%).

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

The between-worker component of exposure variance was generally quite small for the concrete reinforcement tasks. In 13 of the 27 analyses, no variability in exposure was explained by the effect of worker. The between-worker component of exposure variance was less than 10% of the total exposure variance in 6 of the 27 exposure-task combinations, and exceeded the within-worker variability in only 1 case (arms at or above shoulder height during vertical-wall-rebar construction) (Table 34).

Similar results were found for the laborers' jacking-pit construction tasks. No variability in exposure variance was found in 20 of 35 analyses (no exposure to power-tool use during miscellaneous work reduced the number of analyses by 1). The between-worker component of variance exceeded the within-worker variance in 4 cases (MMH during top work and exposures to non-neutral trunk postures, flexed trunk postures and load handling during manual excavation) (Table 35).

For the most part, very little exposure variance was explained by differences among workers for the carpenters' form-construction tasks. No variability in exposure was explained by the term of worker in 15 of the 26 exposure-task combinations (again, no analysis could be performed on power-tool use during 1 task). For a few task-exposures combinations, there was a large between-worker exposure variance component. These included exposure 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, all having more between-worker than within-worker exposure variance (Table 36).

3. Evaluation of Number of Observation Days for Reliable Exposure Assessment

Initial Evaluations

There were 5 to 6 days of group exposure data (depending on the task) for the bootstrapping of group exposure frequencies in the 6 original concrete reinforcement analyses. Six to 10 days of data were available for the bootstrapping of the group exposure frequencies in the jacking-pit construction tasks. Only the carpentry task of form erection had several days in which at least 40 observations were made on multiple workers. Measurements were available for 4 days on a total of 7 workers during this task. The data used for the 18 original analyses are summarized in Appendix V (Tables V-1, V-2, V-3).

Based on these evaluations, 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 (Figures V-1 through V-9).

Selected Exposure Variables

The 4 exposure variables chosen from the 18 for further evaluation were kneeling, squatting or leg bending during manual excavation (high frequency, high variability), trunk flexion during ground-level rebar construction (high frequency, low variability), MMH during pit-wall construction (low frequency, high variability) and power-tool used during ground-level rebar construction (low frequency, low variability). The average number of observations for each of the daily estimates of exposure ranged from 70 to 139 and the minimum number of observations for each day ranged from 40 to 47. Within each task, a total of 9 to 17 workers were evaluated on 6 to 10 days (Table 37).

High Exposure Frequency, High Exposure Variability

The bootstrapping of mean-exposure frequency for kneeling, squatting or bent leg postures during manual excavation resulted in extremely wide confidence intervals for observation periods of 1 to 3 days. There were dramatic improvements in the reliability of the group exposure estimates as assessment periods increased from 1 day (95%-confidence interval = 59%) to 5 days (95%-confidence interval = 30%). The confidence interval decreased very little for observation periods exceeding 5 days. Variability in the distribution of exposure frequencies remained high even for observation periods of 10 days (95%-confidence interval = 30%) (Figure 30a).

High Exposure Frequency, Low Exposure Variability

The bootstrapping of trunk flexion during ground-level rebar construction also resulted in wide 95%-confidence intervals (approximately 30%) in exposure frequency estimates for assessment periods of 1 or 2 days of observation, although confidence intervals were much smaller than those observed in the high-frequency high-variability exposure of kneeling, squatting or leg bending postures during manual excavation. The most dramatic reduction in the 95%-confidence interval for the group frequency of trunk flexion occurred when observation periods increased from 2 to 3 days. The 95%-confidence interval for assessment periods of 6 days was approximately 15%. This was smaller than the 95%-confidence interval obtained after 10 days of assessment for the high-frequency high-variability exposure (Figure 30b).

Low Exposure Frequency, High Exposure Variability

Bootstrapping the mean group frequency of exposure to MMH during pit-wall construction resulted in confidence intervals much smaller than the high frequency variables for all observation periods. In fact, the estimate of the frequency of MMH on observation periods of 1 day had a smaller 95% confidence interval than those obtained for the high frequency variables with 6 (low variability) or 10 days (high variability) of assessment. The largest changes in the 95%-confidence intervals occurred when assessment periods were increased from 1 to 2 days and decreased gradually for longer assessment periods. The 95th percentile confidence limits were 2% and 12% for observation periods of 1 day and were 4% and 7% for observation periods of 7 days (Figure 31a).

Low Exposure Frequency, Low Exposure Variability

The bootstrap showed extremely narrow confidence intervals for all assessment periods. The 95%-confidence interval remained within 1% working time exposed for exposure assessment periods of 1 to 6 days. Therefore, the reliability of the estimates increased very little with increasing days of assessment (Figure 31b).

D. DISCUSSION

1. Task as a Determinant of Exposure

Significant differences in exposure frequency among tasks were found in over one-half of the tests for the three operations evaluated in this study. Often, this was 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. Even when no significant differences in exposure frequency were found among tasks, the observed average differences in exposure frequency for tasks was as much as 8% in concrete reinforcement, 16% in utility-pit construction and 12% in form construction (Tables 31-33). Additionally, it is likely that significant differences among tasks would have been found more frequently if all of a trade's tasks within an operation, rather than a subset of 3 or 4 tasks, could have been evaluated in the models.

For epidemiologic research, an exposure grouping strategy is ideal when there is a large contrast in exposure among groups, the group exposures are as homogenous as possible, and a sufficient number of measurements are made to provide a relatively precise estimate of exposure for each group. This effectively maximizes the between-group variance, minimizes the between-worker variance within group and maximizes the precision of the long-term estimates of exposure (Boleij et al., 1995).

In this study, a trade's tasks during a construction operation 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 the many different ergonomic exposures studied here (i.e., the ideal grouping strategy for one exposure variable would be different than that of another exposure variable). 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 differences in exposure frequency often observed here among tasks provide evidence supporting the task-based strategy as a way to enhance the characterization of exposure for groups (i.e., workers performing the same task rather than workers of the same trade) and the level of detail in the assessments needed for the development of the appropriate controls designed to alleviate problems associated with specific work tasks.

2. Between-worker and Within-worker Components of Variance for Tasks

When the between-worker and within-worker components of exposure variance were examined for each of the tasks, little or no exposure variability was explained by the effect of worker in 67% of the evaluations. The between-worker variance component exceeded the within-worker variance component in only 11% of the tests. This indicates 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.

The data analyzed for this study were not originally collected with the intention of studying the between-worker and within-worker sources of exposure variability in construction tasks. Precise estimates of daily exposures for many workers over a large number of days would allow a comprehensive evaluation of the within- and between-worker components of exposure variability. For this study, the daily task-based exposure frequency estimates for workers were often based on a small number of observations resulting in poor precision (potentially high measurement error). Additionally, both the number of workers and number of measurements on workers were often quite small.

The within-worker variance included all of the exposure variability not explained by worker, such as differences in exposure due to daily changes in the work characteristics (e.g., scheduling demands and the physical characteristics of the construction site) and the error in measuring an individual's daily exposure. Therefore, the lack of precision in the exposure measurements may have, in some cases, deflated the true estimate of exposure explained by the effect of worker (i.e., between-worker effect) and inflated the within-worker exposure variance.

There is limited evidence suggesting that the effect of worker increased with increasing exposure measurement precision. For manual excavation, daily-exposure estimates were calculated with close to 80 observations, allowing reasonably precise measures of exposure frequency. For this task, the effect of worker explained no exposure variance for 3 of the 9 exposures and very little exposure variance for 2 additional tasks For three exposures (33%), however, the variance explained by worker exceeded 50% of the total exposure variance. While the results for manual excavation suggest that the between-worker component of variance may have been underestimated for some exposures during some tasks, the fact that over half of the exposures for manual excavation had a small between-worker variance component suggests that it is likely that the within-worker variance component may often be attributed, at least in part, to day-to-day exposure variability (not measurement error). Unfortunately, the actual amount of variance attributed to daily differences in exposure could not be estimated with the data in this study.

3. Exposure-Days Needed for Reliable Task-Specific Estimates

The results of the bootstrapping procedures used in this study clearly illustrated the importance of evaluating ergonomic exposures for groups of workers on multiple days to improve the reliability of the exposure estimate when exposure frequencies are high. The confidence intervals narrowed the most with longer observation periods for the high exposure frequency variable having high variability in the first 2 days of assessment. For the high-frequency (> 25%) exposures, even observation periods exceeding 6 days usually produced 95%-confidence intervals that exceeded 10%, and only marginal improvements in the reliability of the exposure frequency measurement were obtained with observation periods exceeding 5 days. When the exposure frequency was low (< 8%), the 95%-confidence interval was much narrower, particularly for the low variability exposure.

The need to perform assessments on multiple days to obtain 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 a reliable exposure estimates that do not rely heavily on statistical assumptions about the population distribution are rarely discussed.

The most important limitation of the bootstrapping approach used in this study was the number of observation days from which the resamples were drawn. The data in the bootstrap are assumed to be an unbiased sample (i.e., the exposures observed in those tasks are representative of what would have been observed over a longer observation period) and an empirical distribution constructed from the original sample is intended to provide the best estimate of the population distribution of the statistic. While the population of mean daily-grouped exposure for workers performing the same task is close to a continuous function, the empirical distribution of the original sample is a discrete function which more closely approximates the population distribution with an increasing number of daily-group measurements. 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 number of observation days available for bootstrapping was relatively small for all of the tasks in this study. Confidence intervals for average group exposures were derived from a maximum of 10 observation days and a minimum of 4 observation days. While these conditions did not precisely approximate the true distribution of exposures within task, they represented the best approximation of the true group daily exposure for the construction tasks examined. The bootstrapped confidence limits for the measurement of exposures most likely did not accurately approximate the true confidence limits. Nevertheless, since the same potential bias in the empirical probability distribution would be present for all of the different observation days, the shape of the curves representing the confidence intervals for the exposure measurement on different days would likely remain the same. Therefore, this approach should still allow a valid evaluation of the number of days needed to improve group estimates of exposure.

Additionally, the bootstrap approach could not be used to evaluate the number of workers necessary for a reliable estimate of group exposure because the number of observations made on individual workers within task on a specific day was often quite small, resulting in very poor exposure estimates for individuals. Although the within-worker variance of exposure often greatly exceeded the between-worker variance of exposure within task, exposures among workers were not necessarily equal. Individual differences in physical characteristics (e.g., anthropometry and age) and work practices (e.g., modifications to tools used and differences in postures assumed during work activities) may be sources of inter-worker variability in exposure. Therefore, it is suggested that observations be made randomly on as many workers as logistically feasible (i.e., as many workers as possible in a given day without drastically inhibiting the rate of data collection). In this way, the data collected will more likely be representative of all the workers who perform the task.

Another limitation of this analysis was that the minimum number of observations made on each day for a reliable estimate of long-term exposure was not determined. In this study, daily group task-based estimates of exposure were determined from a minimum of 40 observations and, on average, were based on approximately 90 observations. Assuming that the distribution of exposure within task for the group was normal, observations were made throughout the work day and the true exposure frequency was 50% (the worst precision case), the 95%-confidence interval of the exposure measure would be a maximum of $\pm$ 15% and an average of $\pm$ 10 %. These measures, therefore, allow reasonably good estimates of daily group exposure frequency (so that the between-day exposure variability for groups of workers can be assessed reasonably well) and are also within logistical data collection limits (i.e., 1 observer can usually make enough observations on a group of workers throughout the course of a day to have reasonably precise exposure estimates for the major tasks).

4. Other Methodological Limitations

There are several additional limitations related to the use of the PATH method for the assessment of ergonomic exposures that should be mentioned. First, only relatively broad categories of exposures to awkward body postures are estimated with PATH. Additionally, only the duration of each exposure category is measured (as a percent of working time) and the actual frequency of ergonomic exposures is not recorded (as motions or exertions per unit time). Because observations are made at discrete intervals rather than continuously, the sequence of activities is also lost and rare events such as extremely heavy manual handling may be missed. Other measures may provide useful exposure data (e.g., number of heavy lifts per day during a task). The patterns of exposure variability for other exposure measures may be different and the sampling strategies discussed in this chapter may not apply to such measures.

E. CONCLUSIONS

The results of the study demonstrated that exposures often vary significantly among tasks, indicating that the task-based approach can be used to improve exposure assessment efforts and provide information needed for the development of controls. 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 (in addition to measurement error). This suggests that characterizing exposures for tasks on multiple days may be important for a reliable estimate of exposure. When daily-group exposures with high frequency were bootstrapped, the reliability of the exposure estimates usually improved dramatically as assessment periods approached 5 to 6 days. There were only marginal improvements in the reliability of the assessment for periods greater than 6 days, and the 95%-confidence intervals for the high exposure frequencies remained relatively high even for observation periods exceeding 6 days. These results were particularly true for the high-frequency exposure having high between-day variability. When daily group exposures with low frequency (< 8%) were bootstrapped, reliable group estimates of exposure were obtained with observation periods of 1 or 2 days. Understanding how the length of an observation period affects the reliability of the exposure estimate has important implications for the evaluation of exposures and controls in ergonomics research.

F. RECOMMENDATIONS

1. Because exposures often varied among tasks within an operation, the task-based approach should continue to be used for the assessment of ergonomic exposures in highway construction.

2. Observation periods of at least 6 to 10 days are recommended for high frequency exposures (> 25%), particularly when the between-day variability of exposure is high. While only marginal increases in the reliability of the assessment were observed for periods exceeding 6 days, it may be necessary to perform longer assessments to reach a desired level of reliability. Assessment periods of 2 or 3 days may be adequate for low frequency exposures, particularly if the between-day exposure variability is low.

3. Two days of initial exposure assessment for an initial estimate of the frequency and variability of exposure did not always approximate the entire sample of daily group estimates of exposure. When exposures varied greatly in the first two days of assessment, the variability of the entire sample also tended to be high. On the other hand, in the high exposure frequency low variability case, the inter-day exposure variance increased with additional days of assessment. This could lead a researcher to choose a short observation period for a variable with relatively high inter-day variability and lead to an unreliable estimate of exposure frequency within task. It is therefore recommended that no fewer than 3 or 4 days of exposure data be used in the estimate the inter-day variability in exposure to determine the appropriate observation period.

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. Such an approach would reduce the amount of extraneous data collected and analyzed, as well as the cognitive requirements during the remaining observational periods. This would, however, add a level of complexity in the analysis of exposures, requiring an evaluation of the frequency and variability of exposures after an initial short assessment period.

van der Beek, A., Kuiper, J., Dawson, M., Burdorf, A., Bongers, P., and Frings-Dresen, M. (1995). Sources of variance in exposure to non-neutral trunk postures in varying work situations. Scandinavian Journal of Work, Environment & Health, 21(2): 215-222.

Winkel, J., and Mathiassen, E. (1994). Assessment of physical work load in epidemiologic studies: concepts, issues and operational considerations. Ergonomics, 37(6): 979-988.

TABLE 30

Summary of data collected for the 3 highway construction operations

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
Utility Pit Construction			
Top Work	709	7	9
Pit Wall Construction	563	9	10
Manual Excavation	1416	10	13
Miscellaneous	531	10	10
Form Construction			
Building Forms in a Shop	322	4	6
Building Forms on Site	187	8	8
Form Erection	334	7	7

TABLE 31
Summary of data used for the mixed-effects and random-effect models for the concrete-reinforcement tasks

Exposure	Ground-level Rebar Construction	Vertical Wall Rebar Construction	Preparation Work
Non-neutral Trunk**			
# workers	6	7	5
# indiv. measures of exp.	20	20	15
mean obs./exp. measure	19	17	18
mean exposure (% time)	**52.0**	**38.9**	**32.3**
Flexed Trunk**			
# workers	6	7	5
# indiv. measures of exp.	20	20	15
mean obs./exp. measure	18	18	18
mean exposure (% time)	**41.0**	**27.8**	**24.9**
Laterally Bent or Twisted Trunk			
# workers	6	7	5
# indiv. measures of exp.	20	20	15
mean obs./exp. measure	18	18	18
mean exposure (% time)	**28.2**	**22.4**	**20.3**
Load Handling			
# workers	6	6	5
# indiv. measures of exp.	20	17	15
mean obs./exp. measure	18	18	18
mean exposure (% time)	**18.9**	**14.2**	**19.2**
Arm(s) at or above Shoulder Height			
# workers	6	7	5
# indiv. measures of exp.	20	20	15
mean obs./exp. measure	18	18	18
mean exposure (% time)	**6.2**	**8.9**	**7.7**
Kneeling, Squatting or Leg Bending**			
# workers	6	7	5
# indiv. measures of exp.	20	20	15
mean obs./exp. measure	18	18	18
mean exposure (% time)	**34.8**	**16.6**	**12.6**
Hand-tool Use*			
# workers	6	7	4
# indiv. measures of exp.	20	18	11
mean obs./exp. measure	18	19	20
mean exposure (% time)	**15.6**	**11.2**	**3.2**
Power-tool Use**			
# workers	5	7	4
# indiv. measures of exp.	16	18	11
mean obs./exp. measure	17	17	22
mean exposure (% time)	**0.5**	**3.0**	**9.7**
MMH**			
# workers	6	7	5
# indiv. measures of exp.	20	20	15
mean obs./exp. measure	18	18	19
mean exposure (% time)	**28.7**	**12.1**	**18.9**

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

TABLE 32
Summary of data used for the mixed-effects and random-effect models for the jacking-pit construction tasks

Exposure	Top Work	Wall Construction	Manual Excavation	Miscellaneous
Non-neutral Trunk**				
# workers	2	4	4	4
# indiv. measures of exp.	4	9	11	9
mean obs./exp. measure	107	48	79	32
mean exposure (% time)	**38.3**	**54.5**	**44.4**	**17.5**
Flexed Trunk**				
# workers	2	4	4	4
# indiv. measures of exp.	4	9	11	9
mean obs./exp. measure	107	48	79	32
mean exposure (% time)	**30.8**	**47.5**	**39.1**	**13.5**
Laterally Bent or Twisted Trunk				
# workers	2	4	4	4
# indiv. measures of exp.	4	9	11	7
mean obs./exp. measure	107	48	79	32
mean exposure (% time)	**6.6**	**7.6**	**16.2**	**2.5**
Load Handling**				
# workers	2	4	4	4
# indiv. measures of exp.	4	9	11	9
mean obs./exp. measure	100	45	78	29
mean exposure (% time)	**22.5**	**47.9**	**46.5**	**6.7**
Arm(s) at or above Shoulder Height				
# workers	2	3	4	4
# indiv. measures of exp.	4	7	10	9
mean obs./exp. measure	101	35	85	31
mean exposure (% time)	**9.4**	**3.5**	**6.5**	**6.6**
Kneeling, Squatting or Leg Bending*				
# workers	2	4	4	4
# indiv. measures of exp.	4	9	11	9
mean obs./exp. measure	107	48	79	32
mean exposure (% time)	**27.8**	**46.5**	**40.2**	**20.7**
Hand-tool Use**				
# workers	2	4	4	3
# indiv. measures of exp.	4	9	11	7
mean obs./exp. measure	101	48	78	30
mean exposure (% time)	**10.1**	**23.2**	**36.7**	**10**
Power-tool Use				
# workers	2	3	3	3
# indiv. measures of exp.	4	7	8	7
mean obs./exp. measure	101	48	78	30
mean exposure (% time)	**7.6**	**15.9**	**6.2**	**0**
MMH*				
# workers	2	4	3	4
# indiv. measures of exp.	4	9	8	9
mean obs./exp. measure	101	48	78	31
mean exposure (% time)	**7.1**	**6.6**	**1.1**	**0.8**

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

TABLE 33
Summary of data used for the mixed-effects and random-effect models for the form-construction tasks

Exposure	Form Building in a Shop	Form Building on Site	Form Erection
Non-neutral Trunk**			
# workers	3	3	4
# indiv. measures of exp.	9	7	11
mean obs./exp. measure	30	23	27
mean exposure (% time)	**33.8**	**46.4**	**61.0**
Flexed Trunk			
# workers	3	3	4
# indiv. measures of exp.	9	7	11
mean obs./exp. measure	30	23	27
mean exposure (% time)	**25.7**	**34.3**	**37.0**
Laterally Bent or Twisted Trunk**			
# workers	3	3	4
# indiv. measures of exp.	9	7	11
mean obs./exp. measure	30	23	27
mean exposure (% time)	**18.7**	**18.9**	**44.6**
Load Handling			
# workers	3	2	4
# indiv. measures of exp.	6	4	10
mean obs./exp. measure	22	22	25
mean exposure (% time)	**15.8**	**5.9**	**4.6**
Arm(s) at or above Shoulder Height*			
# workers	3	3	4
# indiv. measures of exp.	8	7	11
mean obs./exp. measure	33	23	27
mean exposure (% time)	**4.2**	**7.8**	**11.4**
Kneeling, Squatting or Leg Bending			
# workers	3	3	4
# indiv. measures of exp.	9	6	11
mean obs./exp. measure	30	24	27
mean exposure (% time)	**15.5**	**25.5**	**24.5**
Hand-tool Use			
# workers	3	2	4
# indiv. measures of exp.	9	5	11
mean obs./exp. measure	29	24	27
mean exposure (% time)	**12.2**	**12.2**	**9.6**
Power-tool Use**			
# workers	3	2	4
# indiv. measures of exp.	9	5	9
mean obs./exp. measure	29	24	26
mean exposure (% time)	**11.6**	**4.4**	**0**
MMH			
# workers	3	3	4
# indiv. measures of exp.	9	7	11
mean obs./exp. measure	30	23	27
mean exposure (% time)	**19.7**	**12.8**	**16.6**

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

TABLE 34

Between-worker and within-worker components of exposure variance for the concrete-reinforcement tasks

Exposure	Ground-level Rebar Construction	Vertical Wall Rebar Construction	Preparation Work
Non-neutral Trunk			
% Between-worker Variance	0	6.9	0
% Within-worker Variance	100	93.1	100
Flexed Trunk			
% Between-worker Variance	0	5.5	3.9
% Within-worker Variance	100	94.5	96.1
Laterally Bent or Twisted Trunk			
% Between-worker Variance	0	0	18.4
% Within-worker Variance	100	100	81.6
Load Handling			
% Between-worker Variance	0.6	7.0	8.2
% Within-worker Variance	99.4	93.0	91.8
Arm(s) at or above Shoulder Height			
% Between-worker Variance	0	59.5	0
% Within-worker Variance	100	40.5	100
Kneeling, Squatting or Leg Bending			
% Between-worker Variance	31.2	9.6	0
% Within-worker Variance	68.8	90.4	100
Hand-tool Use			
% Between-worker Variance	0	0	0
% Within-worker Variance	100	100	100
Power-tool Use			
% Between-worker Variance	20.1	0	47.4
% Within-worker Variance	79.9	100	52.6
MMH			
% Between-worker Variance	0	10.0	29.0
% Within-worker Variance	100	90.0	71.0

TABLE 35

Between-worker and within-worker components of exposure variance for the jacking-pit construction tasks

Exposure	Top Work	Wall Construction	Manual Excavation	Miscellaneous
Non-neutral Trunk				
% Between-worker Variance	0	0	59.0	0
% Within-worker Variance	100	100	41.0	100
Flexed Trunk				
% Between-worker Variance	0	0	62.0	0
% Within-worker Variance	100	100	38.0	100
Laterally Bent or Twisted Trunk				
% Between-worker Variance	0	0	13.2	0
% Within-worker Variance	100	100	86.8	100
Load Handling				
% Between-worker Variance	0	0	64.1	10.7
% Within-worker Variance	100	100	35.9	89.3
Arm(s) at or above Shoulder Height				
% Between-worker Variance	0	0	0	21.5
% Within-worker Variance	100	100	100	79.5
Kneeling, Squatting or Leg Bending				
% Between-worker Variance	0	0	25.1	0
% Within-worker Variance	100	100	74.9	100
Hand-tool Use				
% Between-worker Variance	0	0	46.2	13.7
% Within-worker Variance	100	100	53.8	86.3
Power-tool Use				
% Between-worker Variance	44.6	0	0	n/a
% Within-worker Variance	55.4	100	100	n/a
MMH				
% Between-worker Variance	70.2	19.1	0	81.7
% Within-worker Variance	29.8	80.9	100	19.3

TABLE 36

Between-worker and within-worker components of exposure variance for the form-construction tasks

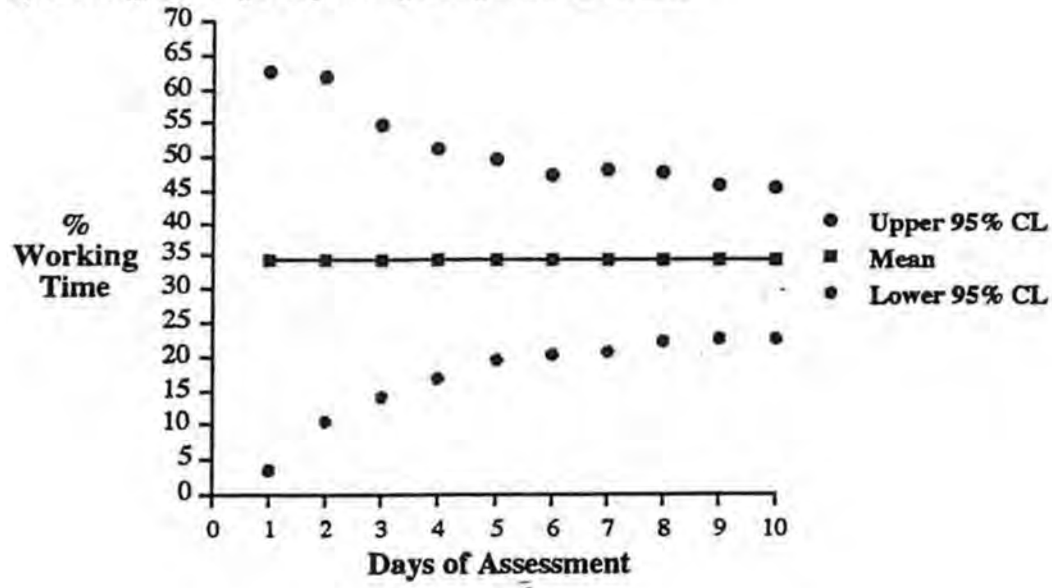
Exposure	Form Building in a Shop	Form Building on Site	Form Erection
Non-neutral Trunk			
% Between-worker Variance	29.0	0	0
% Within-worker Variance	71.0	100	100
Flexed Trunk			
% Between-worker Variance	48.5	0	48.5
% Within-worker Variance	51.5	100	51.5
Laterally Bent or Twisted Trunk			
% Between-worker Variance	0	0	0
% Within-worker Variance	100	100	100
Load Handling			
% Between-worker Variance	0	74.6	50.7
% Within-worker Variance	100	25.4	49.3
Arm(s) at or above Shoulder Height			
% Between-worker Variance	0	54.7	0
% Within-worker Variance	100	55.3	100
Kneeling, Squatting or Leg Bending			
% Between-worker Variance	13.0	0	34.2
% Within-worker Variance	87.0	100	65.8
Hand-tool Use			
% Between-worker Variance	0	0	86.0
% Within-worker Variance	100	100	14.0
Power-tool Use			
% Between-worker Variance	0	69.4	n/a
% Within-worker Variance	100	30.6	n/a
MMH			
% Between-worker Variance	0	0	16.3
% Within-worker Variance	100	100	83.7

TABLE 37

Summary of the data used in for the bootstrapping of the 4 selected variables

Exposure	Task	Mean 2-Day Exposure Frequency (% time)	2-Day Standard Deviation	Average Obs./Day	Minimum Obs./Day	Total Workers	Total Days
Kneeling, Squatting or Leg Bending	Manual Excavation	37.0	34.2	139	40	10	10
Trunk Flexion	Ground Level Rebar	50.3	1.1	94	47	17	6
MMH	Pit Wall Construction	7.3	5.45	70	45	9	7
Power-tool Use	Ground Level Rebar	0.45	0.6	90	46	17	6

a) Kneeling, squatting or leg bending during manual excavation



b) Trunk flexion during ground-level rebar construction

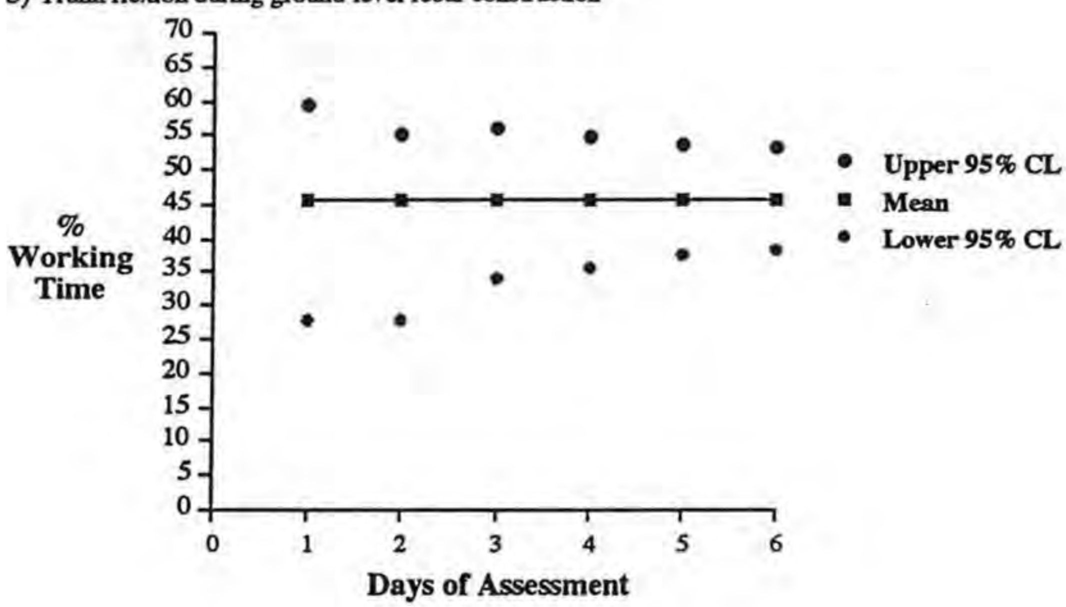


Figure 30. Mean exposure estimates (% working time) using data generated with the bootstrap analysis based on 1000 sets for exposures with: a) high frequency, high variability, b) high frequency, low variability during the first 2 days of observation.

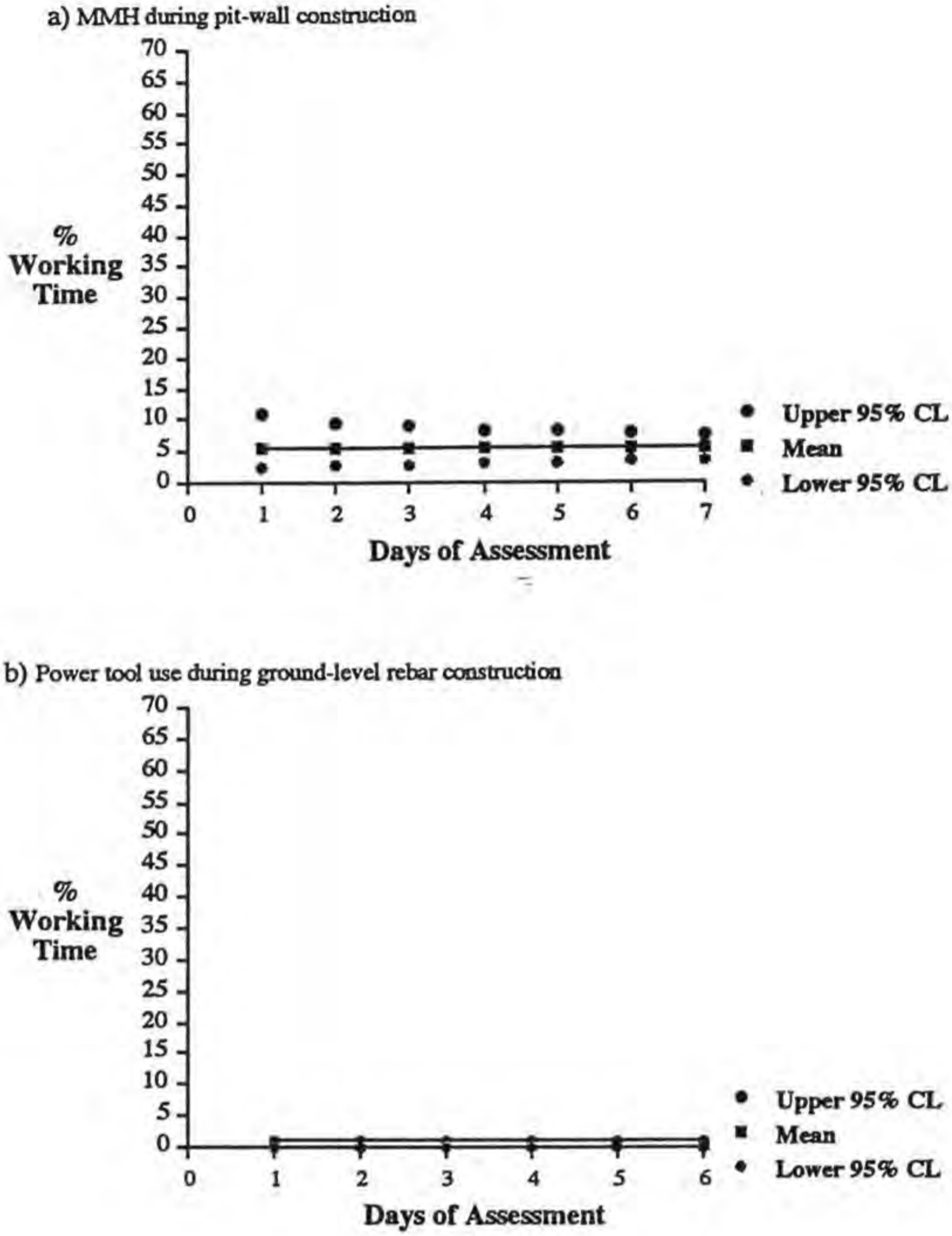


Figure 31. Mean exposure estimates (% working time) using data generated with the bootstrap analysis based on 1000 sets for exposures with: a) low frequency, high variability, b) low frequency, low variability during the first 2 days of observation.

CHAPTER V. CONCLUSIONS

1. Ergonomic Exposure Assessment in Construction Work

The use of direct measurement instrumentation probably offers the most precise and objective measurement of exposures to some ergonomic exposures such as awkward postures. There are, however, some important limitations of these types of methods. The accuracy of the instruments is dependent on proper fitting and calibration procedures. This may require much time on the part of the researcher and worker and demands an additional level of cooperation by the worker beyond what is necessary in observational assessment. The use of electronic measurement equipment may restrict the physical abilities of the worker (e.g., range of motion), possibly introducing an exposure measurement bias when used in the field. There has been very little, if any, research that has scientifically addressed how direct measurement methods alter the physical characteristics of work in occupational settings.

The electronic postural assessment system evaluated in Chapter II and used in Chapter III, however, proved to be valuable for the evaluation of working postures in simulated construction work. The electronic inclinometers provided measurements of shoulder and trunk flexion without calibrating for individuals. They were attached rather easily to the arms and trunk of workers with Velcro and tape and measured shoulder and trunk flexion accurately under static conditions.

While the electronic inclinometers are sensitive to accelerations, shoulder posture recorded by the inclinometers during hand-arm intensive tasks (e.g., sweeping dirt, shoveling crushed rock, placing bricks on a platform) were consistent with approximations of shoulder postures made from an evaluation of videotape (i.e., there were no serious inconsistencies in measurements based on a review of the video tape). Although it is not clear which method, if either, should be considered as the "gold standard", the agreement is reassuring.

The use of the electronic inclinometers for the measurement of knee flexion, however, is not as beneficial or practical. Fitting and calibrating the electronic inclinometers to measure knee flexion takes approximately 15 minutes. Measurements must also be synchronized carefully with videotape to allow the inclinometer data to be cross-referenced with the videotape. The electronic inclinometer data for only these standing postures are then used to measure knee flexion. The data reduction and management process is extremely labor-intensive and time-consuming. Considering these limitations, and the fact that knee flexion is not measured very precisely with the electronic inclinometers, it is recommended that these instruments be used only when the exposure to knee flexion is anticipated to be an important contributor to the loading on the knee during a work activity. Fortunately, kneeling and squatting postures, which are more likely to affect the knee tissues, can be identified quite easily by either visual real-time observation or video analysis.

Trunk lateral bending and torsion were predicted accurately from measurements of lumbar posture recorded by the LMM using simple calibration procedures. The measurements of trunk posture were important for the evaluation of the observational methodologies. However, the LMM was designed specifically to evaluate the postures, velocities and accelerations of the lumbar spine. It is not yet clear whether postures and motions of the entire trunk or those of the low back are more predictive of low back injury, although the high correlation between trunk lateral bending and torsion and lumbar lateral bending and torsion suggests that both sets of exposures are likely to have similar associations. Given that the LMM was designed specifically for the assessment of low back exposures, its use for characterizing trunk postures is recommended only for validity studies such as the one described in Chapter III.

The use of observation methods such as PATH alleviates some of the potential pitfalls of the electronic measurement methods. Some of the specific logistical advantages of PATH are that it allows a systematic characterization of exposure frequencies to multiple workers over periods of days or weeks with very little interference with the work. These advantages are extremely important to the evaluation of construction work, where the etiologic relevant ergonomic exposures to workers can be numerous and where the exposure profiles may differ among workers and across days. Additionally, the often harsh environmental conditions would prevent the use of many types of direct measurement equipment.

The results of Chapter IV illustrated that the frequency and variability of an exposure, as well as days of observation, will affect the reliability of an exposure estimate. For low-frequency, low-variability exposures, observations over 2 or 3 days may be adequate for a reliable estimate of exposures, while for high-frequency, high-variability exposures, over 10 days may be required for only a moderately reliable estimate of exposure.

The advantage of measuring multiple exposures simultaneously with PATH, in some ways, imposes an unnecessary burden. In order to obtain reliable estimates of exposure for all of the PATH variables, the assessment strategy must be designed to assess the exposure with the greatest variability. This requires obtaining many more observations than needed to characterize most of the exposures.

Consider, for example, a case where there is extremely low exposure variability among workers and days for 10 of 20 ergonomic exposures and these exposures could be characterized reliably for a task with an observation period of 2 days on 2 workers. Assume that for at least 1 of the remaining variables, that there is extremely high variability among workers and days, and that 10 workers must be observed on 10 days for a reliable assessment of the exposures. A conservative assessment approach would be to measure exposures for all variables over the 10 days for all 10 workers. In this case, the number of observations made on the low variability exposures would be 25 times greater than necessary for a reliable estimate of exposure! When one considers the additional time involved in the data input, management and analysis, it becomes clear that characterizing many exposures simultaneously without an efficient measurement strategy may be extremely time consuming and costly.

Based on the results of this research, several recommendations are made to improve the validity and/or efficiency of future PATH exposure assessment efforts:

1. Record only exposures hypothesized to be of importance (e.g., predictive of injury).
2. Reduce the number of tools and specific activities to be recorded.
3. Evaluate exposure frequency and variance after 3 to 4 days of variance and drop low-frequency low-variability variables, for which reliable estimates of exposure have been obtained, from the data collection.
4. When recording all postural exposures and many activities is required, divide the exposure variables between 2 or more observers.

2. Implications for the Evaluation of Controls

Using a sampling strategy that allows a reliable measure of ergonomic exposure for groups of workers is extremely important when evaluating a control's effect on exposure. Often research in this area is limited to evaluating changes in exposure in laboratory simulations of working conditions. In the laboratory, effects of the variables on exposure can be experimentally controlled or manipulated, so that the variability in the exposure data caused by variables other than those of interest is minimized. One important limitation of this research, however, is a lack of external validity or generalizability (i.e., the effect that a control has in a laboratory may not be the same as in an occupational setting).

Another approach is to evaluate the effect of the control in the occupational setting for which it was intended. The major limitation of this approach is that the effect a control has on exposure may be masked by other potential sources of exposure variability. Understanding the reliability of the measurement method allows researchers to predict how much random variability pre- and post-intervention can be expected in the estimate of exposure. This information can used to predict the magnitude of a control's affect needed to achieve statistical significance or to provide information on the number of workers and days needed to detect a hypothesized reduction in exposure.

The results in Chapter IV have important applications for the evaluation of controls in highway construction work. Because exposures often varied with the job tasks performed, the task-based approach to ergonomic exposure assessment can be used to identify hazardous tasks. Furthermore, the observation time needed for the pre- and post-intervention assessments can be estimated. For example, the evaluation of a control on a high-frequency, high-variability exposure may require more than 10 days pre- and post-intervention.

3. Implications for Epidemiologic Research

In Chapter III, discrete interval observation of arm postures, trunk flexion, kneeling, squatting and climbing closely approximated measurements made with direct postural assessment system. These exposures have been found to be associated with musculoskeletal disorders of the extremities, neck and shoulders and low back and accurate characterization is important for the evaluation of exposure-health outcome relationships in construction work. With the appropriate sampling strategy, accurate estimation of the frequency of the exposures mentioned above can be expected.

The fact that ergonomic exposures often varied among tasks in highway construction work also has important implications for the design of the exposure assessment strategy in epidemiologic studies on construction workers. Using occupation as a surrogate measure, as is often done, may mask the true association between the physical ergonomic exposure and musculoskeletal health outcome as construction workers in the same occupation are likely to have very different exposure profiles, especially when their task distributions differ from one another.

Assuming that task is often an important source of variance in other construction operations and that the between-worker exposure variance component is small compared to other sources of variances (see Chapter IV), it may be desirable to use task-weighted exposure profiles based on group exposure estimates to obtain estimates of exposure for individual workers. For this, exposures for groups of workers performing the same task would be measured for all of the major job tasks performed by a trade. Next, the task distribution for individual workers over a representative period of time would be needed. An individual worker's estimated exposures would be derived from the frequency in which he or she performed each task and the group estimate of exposure for that task.

The usefulness of this approach is highly dependent on the quality of the information on both the estimates of exposure for tasks and of task distributions for individual workers. Reliable estimates of exposure may require a few to many days of assessment for each task that a trade performs. The task distribution of individual workers can be obtained, for example, with questionnaires, daily diaries and direct observations. A combination of diary validated with direct observations may provide a logistically feasible and cautious approach to estimating individual task distributions. More research is needed to determine how sources of error in the task-based assessment of exposure and in the estimation of task distribution affect individual estimates of long-term exposure in epidemiologic study.

4. Areas for Future Research

This research has only begun to address the issues intended to improve exposure assessment in construction and other non-routinized work. Research that would further enhance our understanding of exposure assessment in such environments includes:

1. an evaluation of the electronic inclinometers in dynamic conditions, using a reference method such as a 3-dimensional diode-based postural assessment system.
2. an evaluation of how wearing electronic inclinometers and LMM affects workers' postures.
3. further comparison of PATH and simplified PATH during dynamic and static work, with both inexperienced and experienced observers and for different viewing distances.
4. an evaluation of exposures in a few construction tasks for which precise daily estimates of exposure are obtained on 10 to 20 workers over 20 days. This will allow a more accurate examination of the between- and within-worker components of variability, as well as the appropriate sampling strategy needed, for reliable estimates of individual and group exposures.

5. an evaluation of task-based exposure profiles of individuals that compares these profiles to workers' actual exposures.

APPENDIX I

Informed Consent Forms

Study I: Evaluation of an Electronic Postural Measurement System

Study II: Evaluation of Work Sampling in Construction Work

UNIVERSITY OF MASSACHUSETTS LOWELL
Institutional Review Board
Informed Consent Form: Study I

Date Prepared:	2/1/97	Approved for use by the University of Massachusetts Lowell Institutional Review Board
Project Title:	Work Sampling for the Ergonomic Exposure Assessment of Non-repetitive Work	
Researcher(s):	Victor L. Paquet, M.S.	Signed:______________ IRB Chairperson
	Laura Punnett, Sc.D. (Chairperson)	______________ Date of Approval
		This Informed Consent Form is valid for a period not to exceed one year from the date of approval appearing above.

Purpose
You are being asked to participate in a research study which involves the measuring of body postures. Over long periods of time, awkward body postures are thought to cause injury to the joints of the body. The only way to know how awkward body postures affect the health of workers is to measure these postures accurately. This study will test the accuracy of several devices designed to measure arm, leg and trunk postures.

Procedure and Duration
You are being asked to participate in a study which involves measuring arm, leg and trunk postures over a 5 to 6 hour period. You will be asked to change into a pair of coveralls having devices that measure arm, leg and trunk postures. You then will be asked to assume different postures (e.g., raise your arm to shoulder height). Measurements will be taken with the devices and compared with measurements obtained with standard body posture measurement equipment (i.e., manual goniometer, inclinometer, and protractor).

Risks and Discomfort
There are no significant risks involved in being a participant in this study, though you may experience slight discomfort while holding a specific posture. If this should occur, it will be for a short duration and you will be given time to recover before assuming another posture.

Benefits
There is no direct benefit to you, other than the knowledge that you will be helping to improve measurements of awkward body postures in the workplace.

Refusal or Withdrawal of Participation
Participation in this study is completely voluntary, and your participation, or non-participation, will not affect other relationships (e.g., employer, school, etc.). You may discontinue your participation in this research program at any time without penalty or costs of any nature.

Privacy and Confidentiality
Every precaution shall be taken to protect your privacy and the confidentiality of the records and data pertaining to you in particular, and the research program in general, disclosure of which may contribute to identifying you specifically to persons not related to this research program.

Additional Information

If you do not understand any portion of what you are being asked to do, or the contents of this form, the researchers are available to provide a complete explanation. Questions relating to this research project are welcome at any time. Please direct them to Victor Paquet, the Researcher, or Laura Punnett, Sc.D., the Faculty Adviser, at the following addresses:

Victor Paquet
Dept. of Work Environment
Kitson 200
UMass Lowell — North Campus
Campus Tel.: (508) 934-3347

Dr. Laura Punnett
Dept. of Work Environment
Kitson 200
UMass Lowell — North Campus
Campus Tel.: (508) 934-3269

I have been informed of any and all possible risks or discomforts.

I have read the statements contained herein, have had the opportunity to fully discuss my concerns and questions, and fully understand the nature of my involvement in this research program, and the risks and consequences of my participation.

Participant Date

Researcher Date

Faculty Advisor Date

UNIVERSITY OF MASSACHUSETTS LOWELL
Institutional Review Board
Informed Consent Form: Study II

Date Prepared:	2/1/97
Project Title:	Work Sampling for the Ergonomic Exposure Assessment of Non-repetitive Work
Researcher(s):	Victor L. Paquet, M.S. Laura Punnett, Sc.D. (Chairperson)

Approved for use by the
University of Massachusetts Lowell
Institutional Review Board

Signed:______________
IRB Chairperson

____
Date of Approval

This Informed Consent Form is valid for a period not to exceed one year from the date of approval appearing above.

Purpose
You are being asked to participate in a research study which involves measuring body postures during construction work. Over long periods of time, awkward body postures are thought to cause injury to the joints of the body. The only way to know how awkward body postures affect the health of workers is to measure these postures accurately while people work. This study will test the accuracy of an observational postural assessment method for measuring body postures during construction work.

Procedure and Duration
The study should take approximately 2 hours to complete. You will be asked to change into a pair of coveralls which have devices that measure arm, leg and trunk postures. You will then be asked to assume different body postures (e.g., hold arms at shoulder height) so that the devices can be calibrated. You will then perform construction tasks (e.g., manual handling of construction materials, sweeping, etc.). Measurements will be taken with the devices and compared with measurements obtained with an observational assessment method. You will also be video-taped during the study and this videotape will be used to identify the presence of various leg postures (i.e., kneeling , squatting, etc.) during the construction tasks. The videotape will be kept confidential and will be destroyed within 2 years from the day of recording.

Risks and Discomfort
There are no significant risks involved in being a participant in this study, though you may experience slight discomfort or fatigue while performing the construction tasks. If this should occur, you will be allowed to rest before continuing with the construction tasks.

Benefits
There is no direct benefit to you, other than the knowledge that you will be helping to improve measurements of awkward body postures in the workplace.

Refusal or Withdrawal of Participation
Participation in this study is completely voluntary, and your participation, or non-participation, will not affect other relationships (e.g., employer, school, etc.). You may discontinue your participation in this research program at any time without penalty or costs of any nature.

Privacy and Confidentiality
Every precaution shall be taken to protect your privacy and the confidentiality of the records and data pertaining to you in particular, and the research program in general, disclosure of which may contribute to identifying you specifically to persons not related to this research program. The videotape will also be kept confidential and will be destroyed within 2 years from the day of recording.

Additional Information

If you do not understand any portion of what you are being asked to do, or the contents of this form, the researchers are available to provide a complete explanation. Questions relating to this research project are welcome at any time. Please direct them to Victor Paquet, the Researcher, or Laura Punnett, Sc.D., the Faculty Adviser, at the following addresses:

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I have been informed of any and all possible risks or discomforts.

I have read the statements contained herein, have had the opportunity to fully discuss my concerns and questions, and fully understand the nature of my involvement in this research program, and the risks and consequences of my participation.

Participant Date

Researcher Date

Faculty Advisor Date

APPENDIX II

Pilot Studies Involving the Preliminary Evaluation of the Direct Postural Measurement System

1. Evaluation of a Calibration System.

A pilot study was conducted to evaluate the accuracy of body posture measurements made with the calibration system. A 5-camera 3-dimensional diode-based postural analysis system (Qualysis AutoGait 3D, Qualysis, Inc., 1995) was used as the reference (Figure II-1). Diodes were placed on the hip and upper portion of the thoracic region of the back for trunk flexion, on the lumbar spine, cervical spine and shoulders to measure trunk lateral bending and torsion, on the acromion process and lateral epicondyle to measure upper arm flexion and with the lateral mid-sections of the knee and upper and lower legs to measure knee flexion. Measurements were made with manual equipment and the diode-based system for one subject while in different trunk, arm and leg postures (Figure II-2). Differences between diode-based system measurements and those obtained with the manual instruments were small, usually within 2 or 3 degrees for trunk and shoulder postures. Differences were slightly larger for knee postures, possibly due to inaccuracies in the placement of the diodes on the legs (Table II-1). These results indicated that the manual instruments used for the calibration of the electronic inclinometers and the LMM provided relatively good measures of body posture, particularly for the trunk and arms.

2. Preliminary Evaluation of the Electronic Inclinometers

A pilot study was conducted to examine the relationship between the voltage outputs of the inclinometers and angle measured with a weighted inclinometer (Figure II-3). The electronic inclinometers were secured to a reference frame having weighted inclinometer and tilted in 10-degree increments over a range of 180 degrees for 5 trials. The average difference between the electronic inclinometers and weighted inclinometer were recorded for each of the angles. The results demonstrated that the relationship between the voltage output and angle relative to gravity was best described by a 3rd-order polynomial equation (Figure II-4). The relationship between the voltages and angles differed slightly between inclinometers (Figure II-5). When these prediction equations were applied to the voltages recorded over a range of 180 degrees, the inclinometers predicted angles relative to gravity to within about 3 degrees of accuracy (Table II-2).

Two pilot tests were completed in order to determine the proper placement of the electronic inclinometers on the upper arms. First, a range of upper arm postures below and above the shoulder (angles measured with a weighted inclinometer and electronic inclinometers simultaneously) were recorded for one subject. The electronic inclinometer was placed in three positions: on the front and in line with the upper arm, on the lateral side and in line with the upper arm, and on the lateral side and perpendicular with the upper arm. Regardless of the inclinometer's position on the arm, the angle relative to gravity was predicted fairly well (Figure II-6). These results were confirmed in a second pilot test with the electronic inclinometer placed on the front lateral portion of the upper arm.

A model of the knee was used to determine the most appropriate placement of the inclinometers on the legs (Figure II-7). Model knee flexion was measured with a weighted inclinometer and the electronic inclinometers. The electronic inclinometers were positioned in three arrangements: on the front and in line with the upper and lower legs, on the front and perpendicular to the upper and lower legs, and on the side and perpendicular to the upper and lower legs. For different knee flexion angles, the difference in voltages between the upper and lower electronic inclinometer was recorded. For each different electronic inclinometer arrangement, the best fit equations that predicted knee flexion from the difference in voltage readings were calculated. Measurements predicted by the electronic inclinometers were compared to those made with the weighted inclinometer. The least measurement error was found when the inclinometers were placed perpendicularly on the side of the upper and lower legs.

This placement was tested in a second pilot study involving 2 subjects. Measurements were made with a manual goniometer and the electronic inclinometers, and the best fit equations were used to calculate the knee flexion predicted from the difference between the voltages recorded by the upper and lower electronic inclinometers. Generally, differences between each of these methods were relatively small (Table II-3).

The electronic inclinometer used to measure trunk flexion was secured to the upper base of the LMM. When the subject stood upright, the electronic inclinometer was approximately perpendicular to gravity. In a pilot test involving 2 subjects, measurements were obtained with a weighted inclinometer and electronic inclinometer simultaneously, and the best fit equations were used to calculate the trunk flexion predicted by the electronic inclinometer. Differences between the methods were small (Table II-4).

3. Preliminary Evaluation of the Lumbar Motion Monitor

In a pilot study involving three subjects, the LMM was used measure trunk lateral bending and torsion. Measurements of side-bending were made with a weighted inclinometer and measurements of trunk torsion were measured with a protractor mounted on the floor, while measurements were made with the LMM. The best fit equations were calculated to predict trunk lateral bending and torsion from lumbar lateral bending and torsion. Generally, differences between measurements were within five degrees (Table II-5).

TABLE II-1

Body postures predicted with the Qualysis Autogait 3D Kinematic Measurement System and manual calibration devices in a pilot study of 1 subject

Body Posture	Qualysis System (deg)	Manual Calibration (deg)	Difference (deg)
	97.8	98	0.2
Right	88.2	90	1.8
Shoulder	61.8	63	1.2
Flexion	44.4	43	1.4
	2.3	3	0.7
	2.8	1	1.8
Right	24.3	31	5.7
Knee	61.3	70	8.7
Flexion	76.7	85	8.3
	133.1	135	1.9
	-2.1	-2	0.1
Trunk	19.1	15	4.1
Flexion	47.9	47	0.9
	53.4	55	1.6
	87.1	89	1.9
	0.6	0	0.6
Trunk	12.7 R	12 R	0.7
Lateral Bending	21.3 R	26 R	4.7
	15.4 L	16 L	0.6
	23.0 L	27 L	4.0
	1.4	0	1.4
Trunk	10.8 R	10 R	0.8
Torsion	22.2 R	20 R	0.2
	12.6 L	10 L	2.6
	18.8 L	20 L	1.2

R = Right, L = Left

TABLE II-2

Angles (deg) predicted by the 8 electronic inclinometers for different angles of forward/backward tilt from the vertical

Weighted Inclinometer (deg)	Channel 0 (deg)	Channel 1 (deg)	Channel 2 (deg)	Channel 3 (deg)	Channel 4 (deg)	Channel 5 (deg)	Channel 6 (deg)	Channel 7 (deg)	ave. dev. (deg)
90 horizontal	92.7	90.2	89.1	89.0	89.6	89.7	89.7	90.4	0.8
100	101.4	98.6	98.0	98.2	97.7	98.0	98.9	98.8	1.6
110	109.1	107.6	107.3	107.2	107.2	107.3	107.5	107.3	2.4
120	117.2	118.1	118.4	118.4	119.3	118.0	117.8	117.0	2.0
130	127.5	130.7	130.9	130.1	130.3	130.5	130.7	128.0	1.0
140	138.4	143.9	144.8	144.8	144.0	143.6	143.2	142.6	3.6
150	149.8	153.5	155.3	155.9	155.4	153.1	154.0	153.3	3.8
160	163.4	164.8	164.6	163.1	164.0	164.7	166.8	163.1	4.3
170	172.3	170.5	169.3	169.0	169.3	170.2	168.6	170.5	0.9
180 vertical down	177.4	170.9	169.8	171.7	171.2	172.3	171.0	175.0	7.6
90 horizontal	91.6	89.5	89.2	89.5	89.5	89.9	89.2	91.4	0.8
80	82.3	80.8	81.3	81.2	80.5	81.4	81.3	82.7	1.4
70	71.5	72.7	72.4	72.8	72.4	72.5	72.6	73.3	2.5
60	58.5	63.2	62.9	62.7	63.2	62.6	63.3	62.0	2.7
50	45.0	50.5	51.2	51.5	51.9	50.4	50.7	49.1	1.5
40	32.1	38.1	39.3	38.9	38.3	38.8	38.2	34.5	2.7
30	22.1	27.1	26.3	26.3	26.4	26.3	25.7	23.8	4.5
20	16.3	16.9	17.4	16.3	17.3	17.1	16.6	16.3	3.2
10	13.4	7.7	7.7	9.6	9.4	9.8	10.0	9.8	1.2
0 vertical up	16.1	6.7	5.9	5.0	4.4	4.6	5.5	11.3	7.4
90 horizontal	91.9	88.2	88.8	88.7	88.9	89.5	88.8	89.6	1.2
average deviation (deg)	3.5	2.6	2.8	2.6	2.5	1.7	2.7	1.7	2.5

TABLE II-3

Knee flexion (deg) measured with a manual goniometer and predicted by the electronic inclinometers for one subject

Manual Goniometer	Electronic Inclinometers	Deviation
0	-6.9	6.9
5	8.4	3.4
10	15.3	5.3
15	17.4	2.4
20	18.5	1.5
25	27.6	2.6
30	28.8	1.2
35	33.4	1.6
40	33.4	6.6
45	53.5	8.5
	average deviation	4.0

TABLE II-4

Trunk flexion (deg) measured with a weighted inclinometer and predicted by the electronic inclinometers for one subject

Weighted Inclinometer	Electronic Inclinometer	Deviation
0	-0.8	0.8
5	5.6	0.6
10	11.4	1.4
15	14.4	0.6
20	20.1	0.1
25	24.6	0.4
30	28.0	2.0
35	36.8	1.8
40	44.5	4.5
45	45.0	0.0
50	49.2	0.8
55	49.0	6.0
60	62.3	2.3
65	66.0	1.0
70	69.8	0.2
75	79.2	4.2
80	77.5	2.5
85	83.0	2.0
90	89.4	0.6
	average deviation	1.7

TABLE II-5

Trunk side bending and torsion (deg) measured with a weighted inclinometer, protractor and LMM for one subject

Side Bending

Weighted Inc.	Predicted LMM	Deviation
0	4.0	4.0
-5 L	-2.1	2.9
-10 L	-10.1	0.1
-15 L	-18.0	3.0
-20 L	-21.5	1.5
-25 L	-24.2	0.8
0	0.5	0.5
5 R	5.8 R	0.8
10 R	10.2 R	0.2
15 R	13.8 R	1.2
20 R	18.1 R	1.8
25 R	23.4 R	1.5
	average difference	1.5

Trunk Torsion

Weighted Inc.	Predicted LMM	Deviation
0	1.7	1.7
10 L	15.1	5.1
15 L	14.2	0.8
20 L	18.0	2.0
25 L	26.4	1.4
0	3.8	3.8
5 R	3.8 R	1.2
10 R	9.2 R	0.8
15 R	10.9 R	4.1
20 R	22.6 R	2.6
	average deviation	2.8

L = Left, R = Right

Figure II-1. A reference frame is used to calibrate the 5 camera diode-based system (Qualysis). This system tracks diodes in space with extreme accuracy.

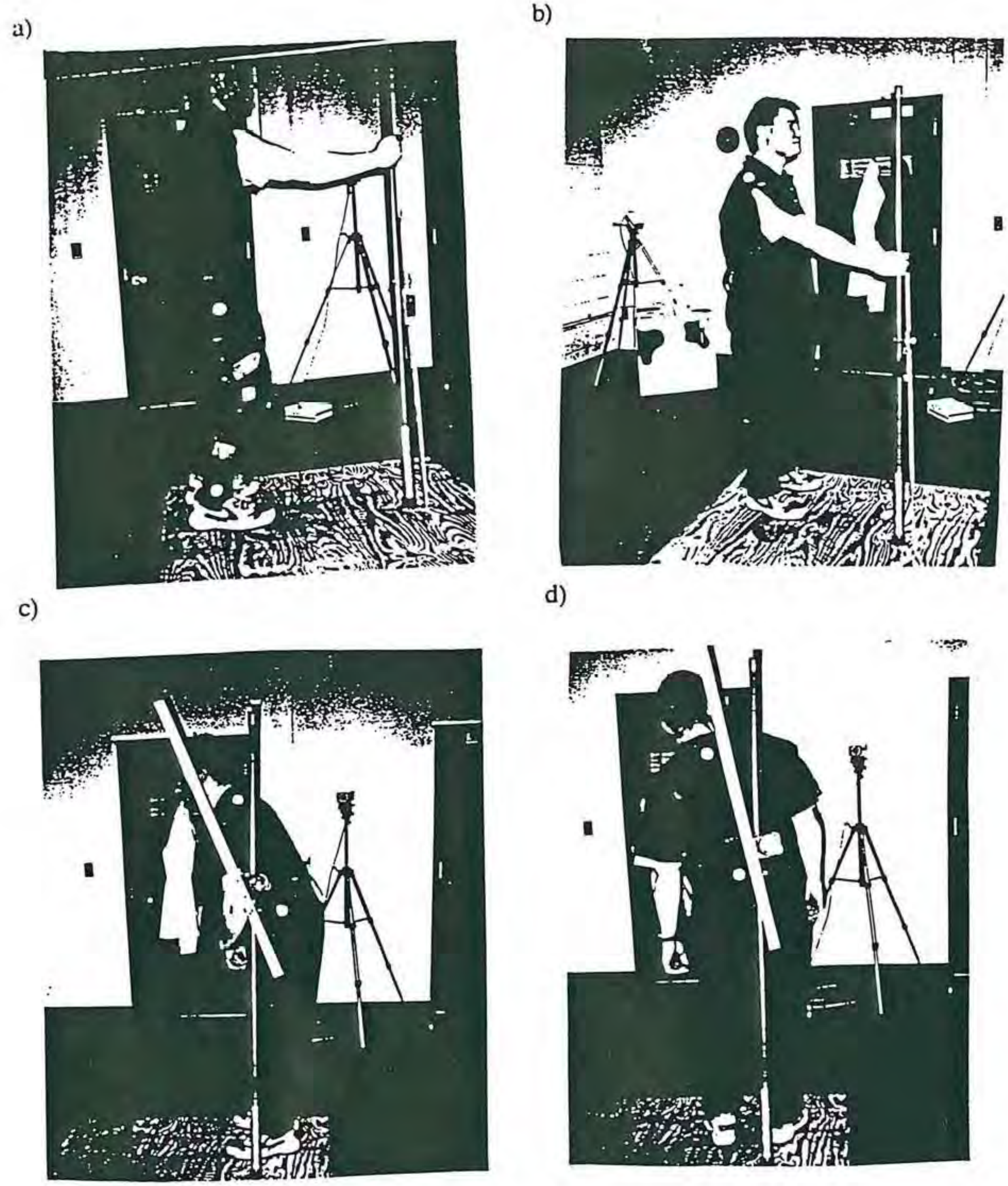


Figure II-2. Measurements were recorded with the Qualysis system and manual calibration instruments simultaneously. Illustrations include: a) subject with knee flexed, b) subject with shoulder flexed, c) subject with trunk flexed, and d) subject with trunk laterally bent.

Figure II-3. The electronic inclinometers were attached to an adjustable frame and tilted in 10 degree increments (measured with a weighted inclinometer). Data from the electronic inclinometers was recorded on a data logger and transmitted to a personal computer.

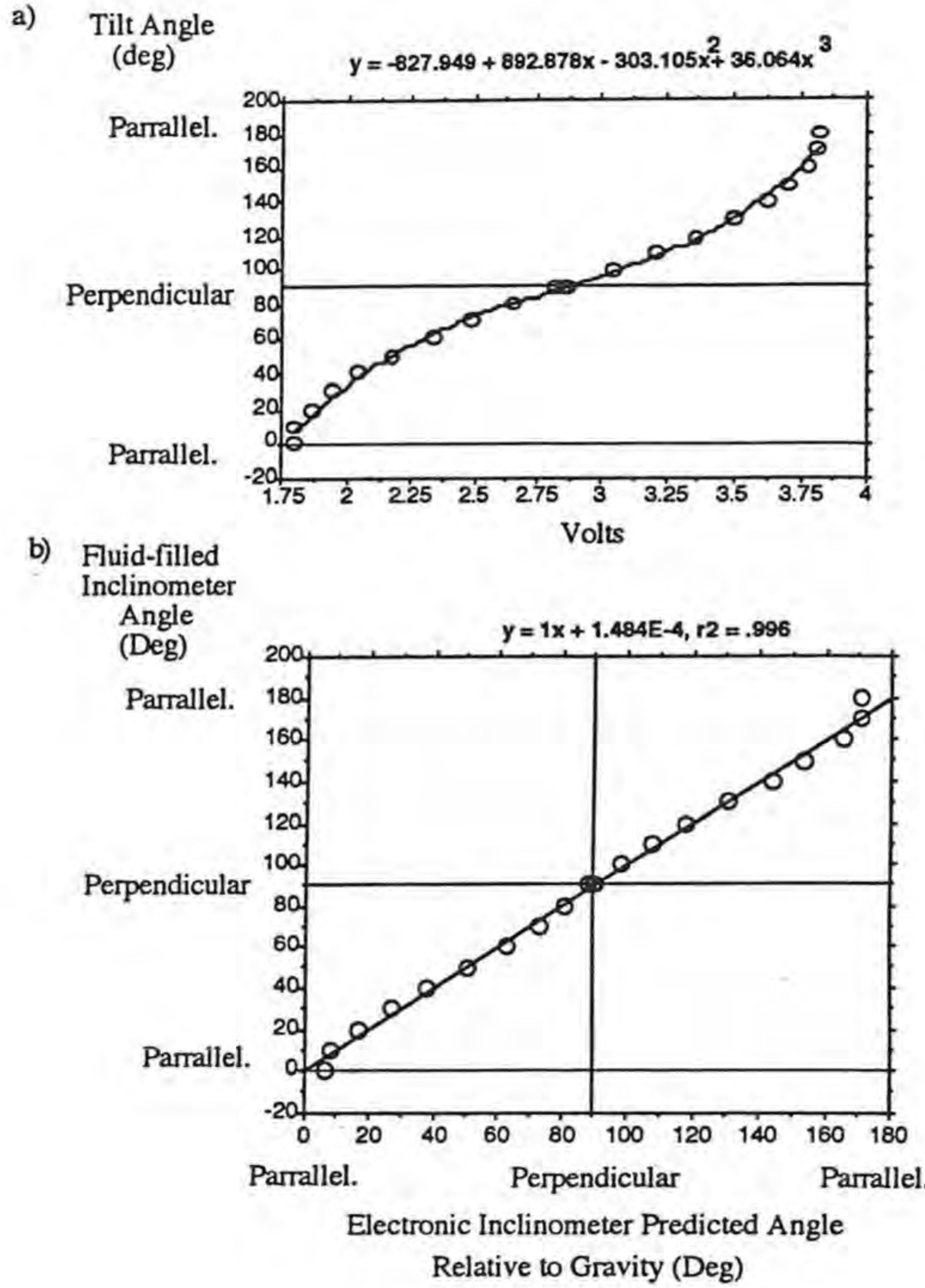
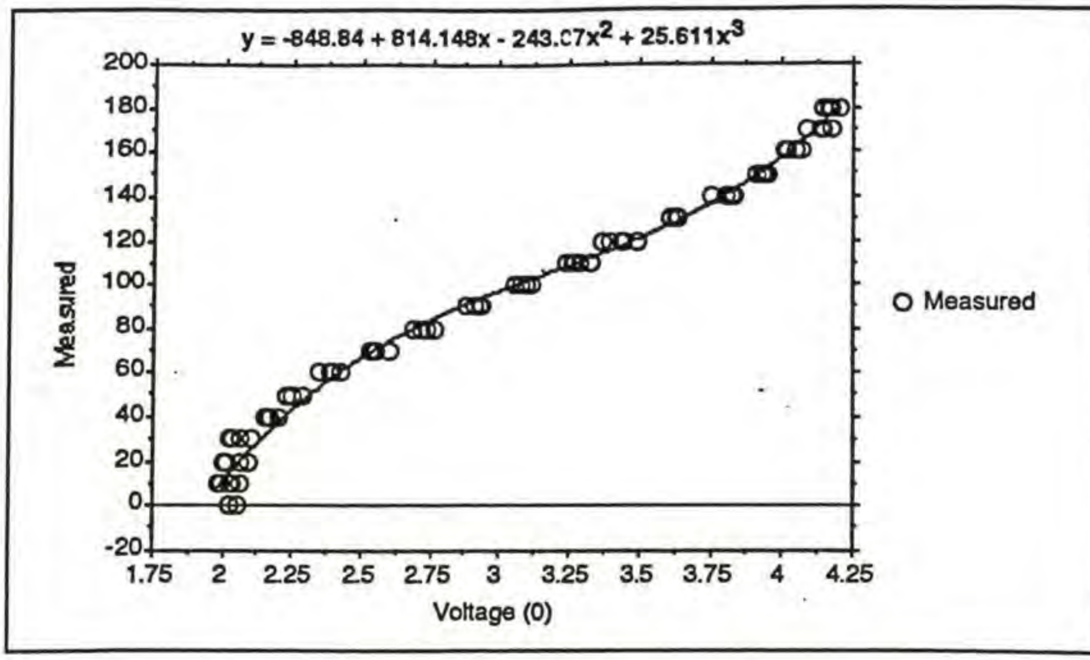


Figure II-4. a) The relationship between each electronic inclinometer's voltage outputs and the angle relative to gravity is best described by a third order polynomial equation. b) The equation is then applied to the voltage outputs to calculate the electronic inclinometer's predicted angle.



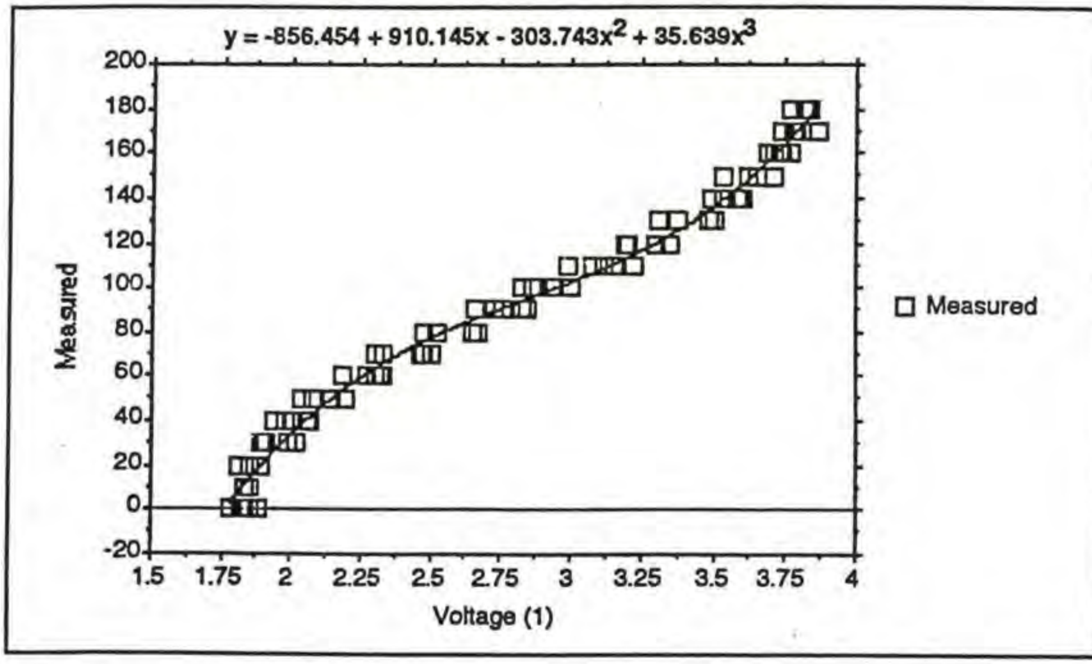
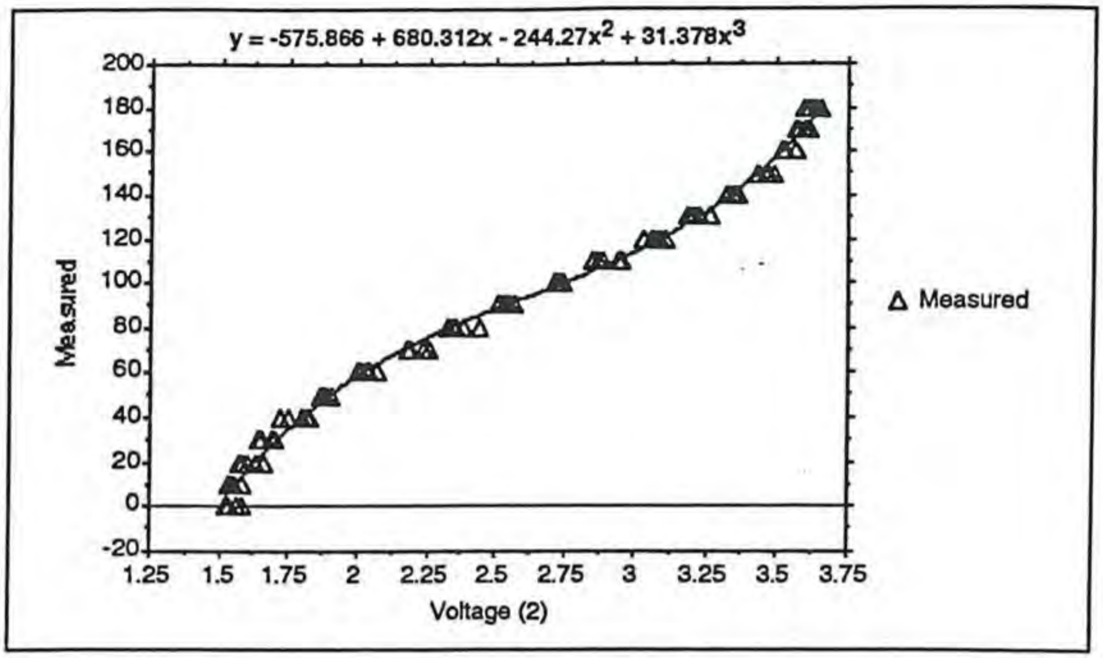


Figure II-5. Calibration equations for the 8 electronic inclinometer channels, Volt (0) - Volt (7), to predict different angles of forward tilt (vertical up = 0 deg., horizontal = 90 deg., vertical down = 180 deg.) determined empirically from 5 trials. Measurements were taken in 10 degree intervals from 0 to 180 degrees forward tilt on a measurement frame (y = predicted tilt angle, x = average voltage recorded from the electronic inclinometers).



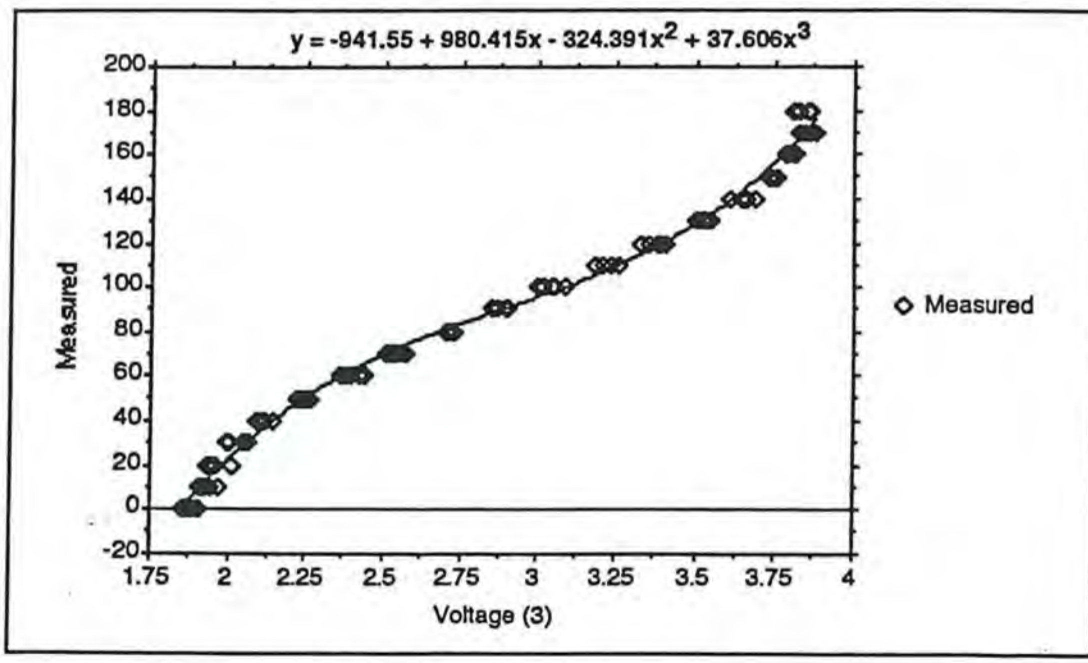
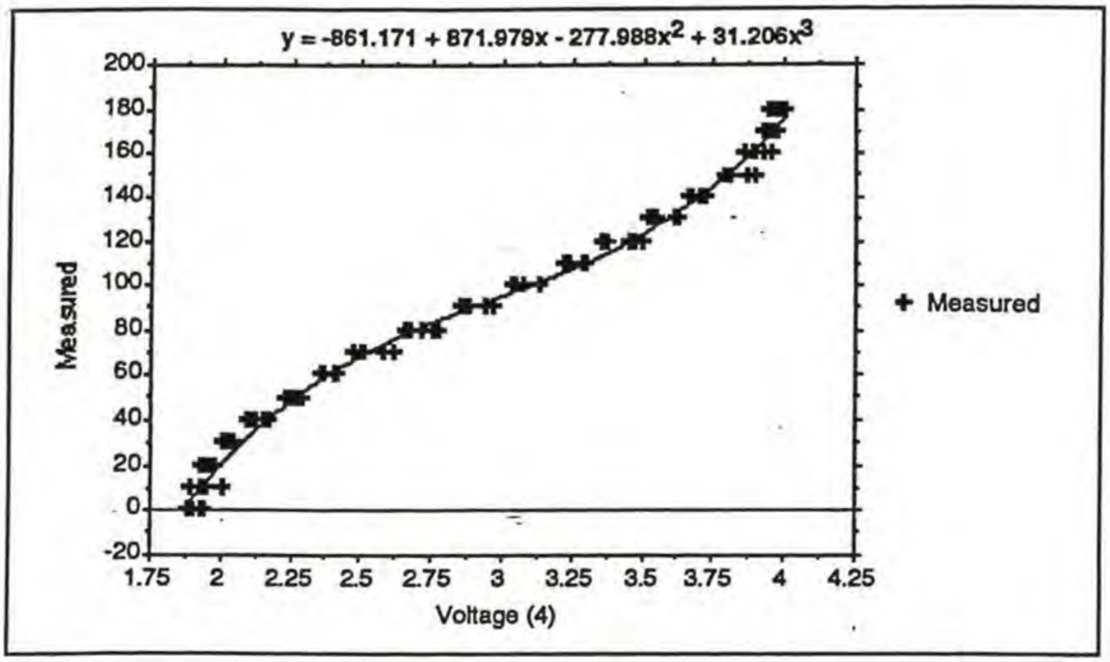


Figure II-5. cont.



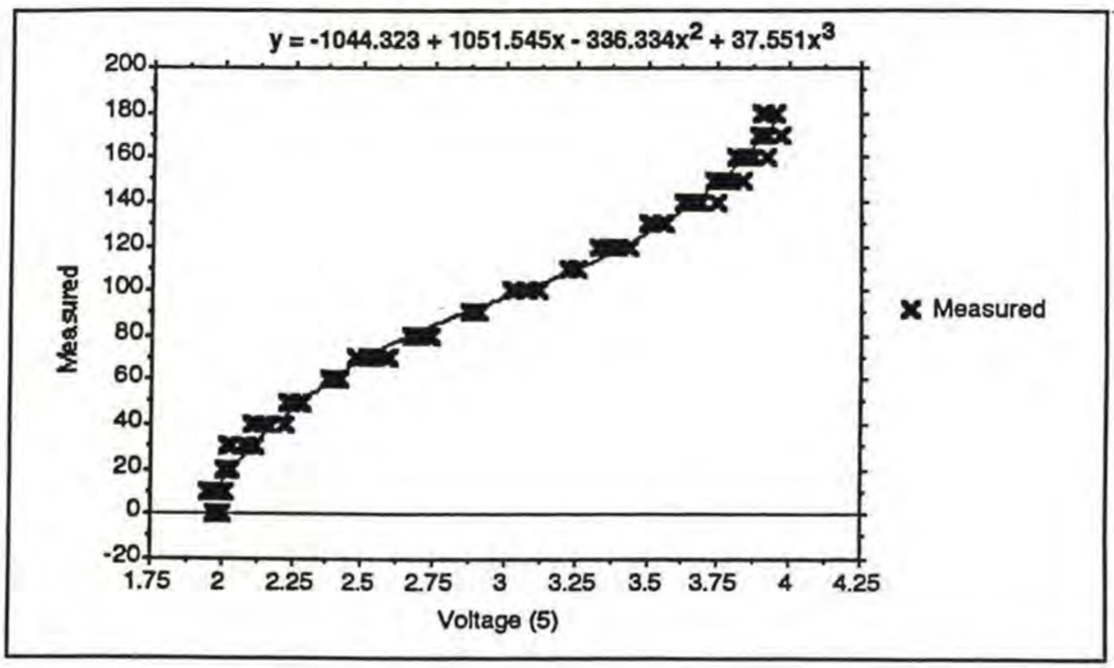
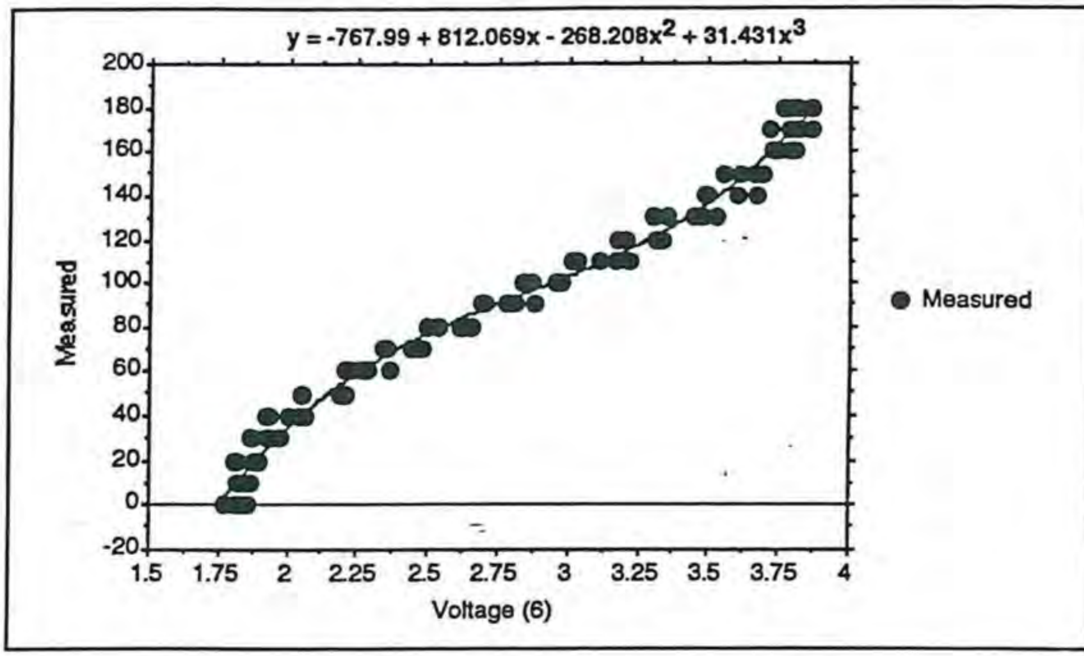


Figure II-5. cont.



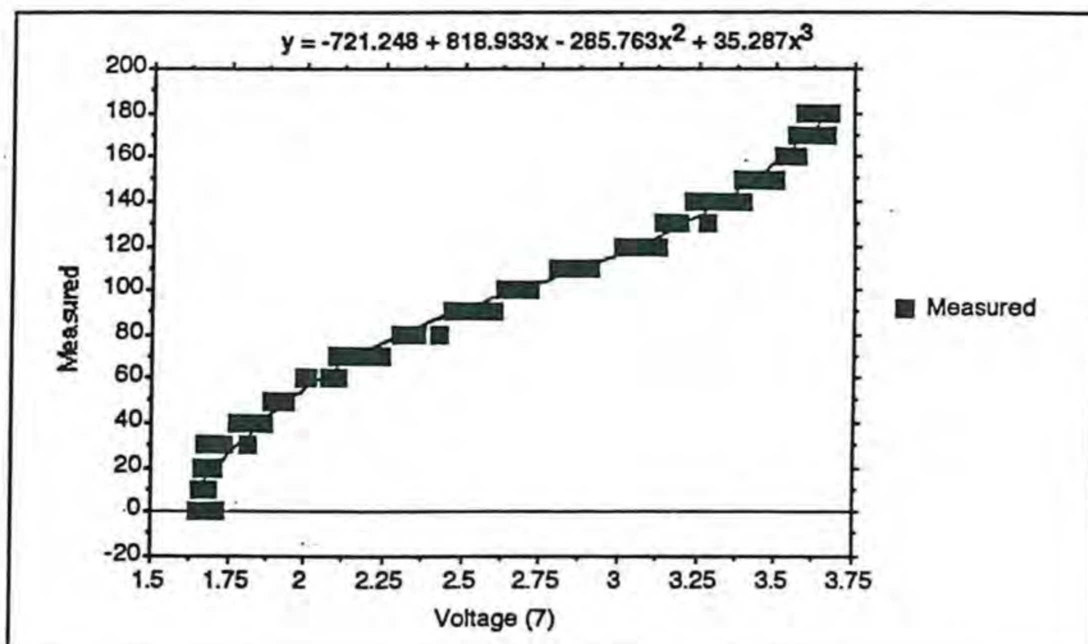


Figure II-5 cont.

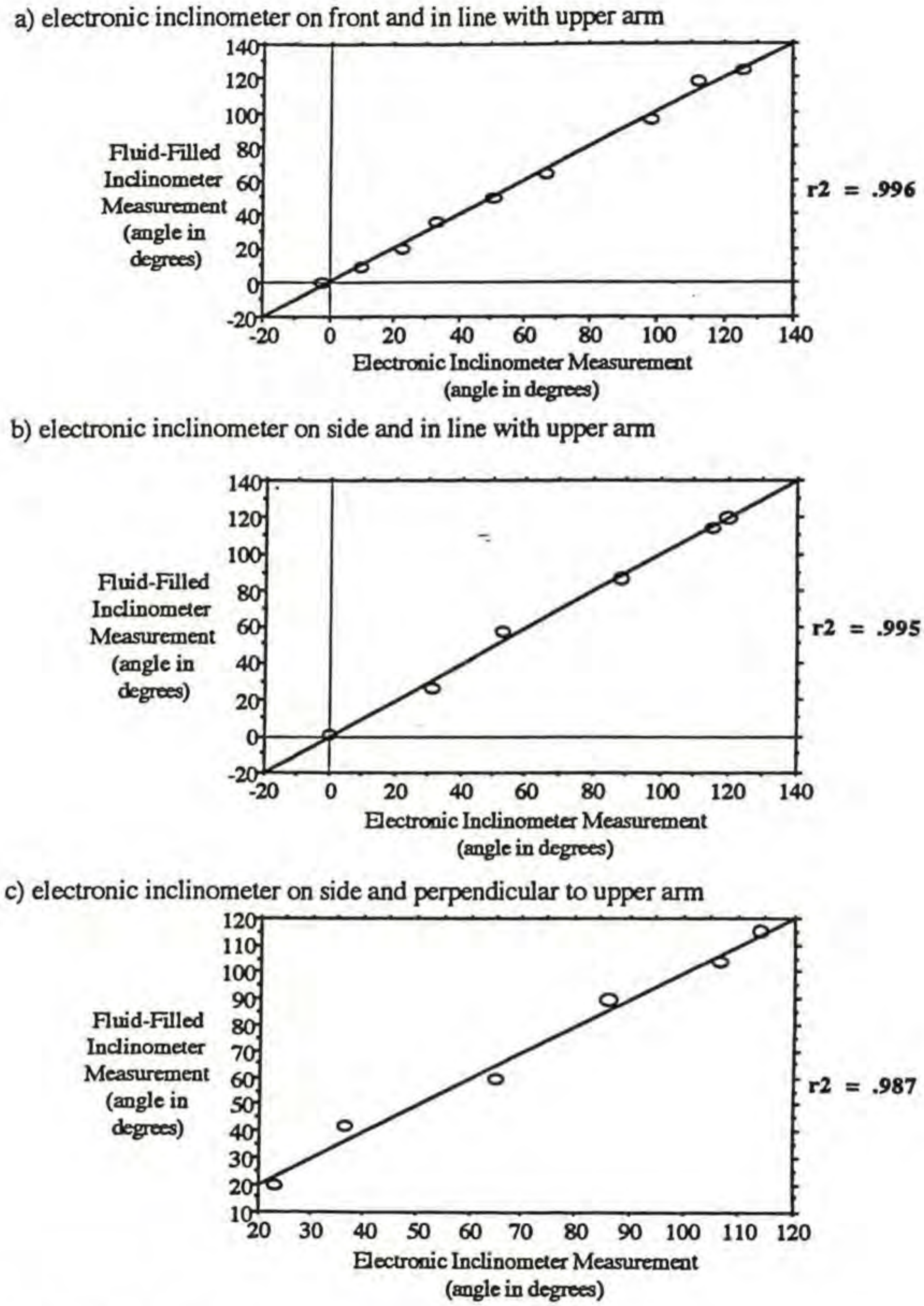


Figure II-6. Upper arm position measured with a weighted inclinometer and predicted by an electronic inclinometer placed on 3 different locations on the arm.

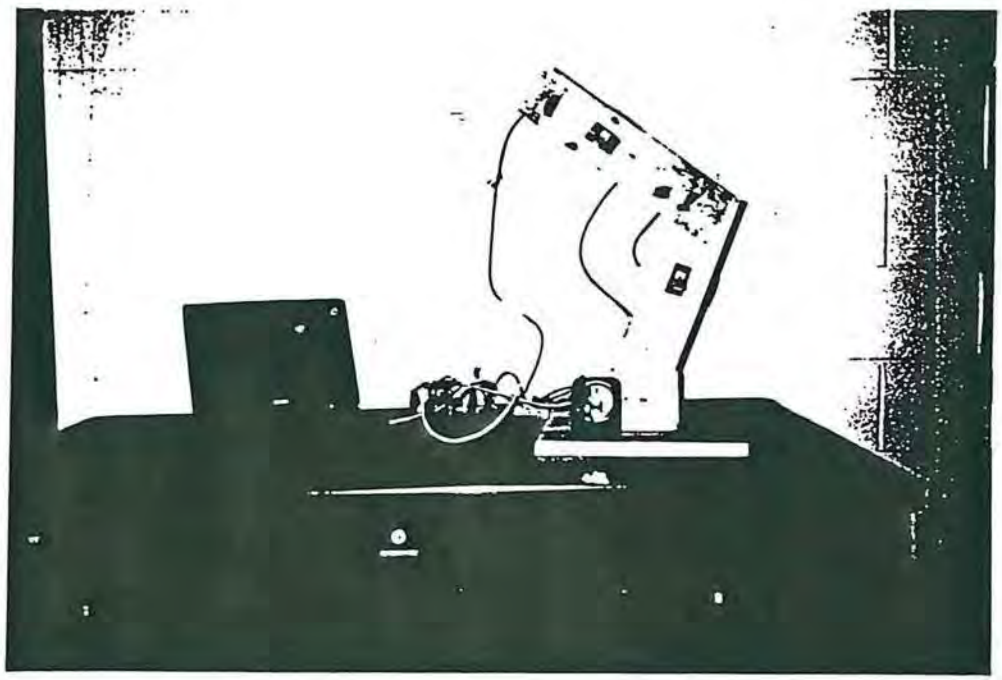


Figure II-7. A model of the knee was used to determine the placement of the inclinometers that minimized the error in predicting knee flexion.

APPENDIX III

Equations Used to Predict Postures in the Evaluation of the Electronic Postural Measurement System

TABLE III-1

Summary of the equations used to predict right and left shoulder flexion for each subject

(y = predicted shoulder flexion in deg., x = inclinometer voltage)

Calibration and Subject	Left Shoulder Flexion (deg.)	Right Shoulder Flexion (deg.)
None*		
Subject 1	$y = 1036.5-910.1x+303.7x^2-35.6x^3$	$y = 1036.5-910.1x+303.7x^2-35.6x^3$
Subject 2	$y = 1036.5-910.1x+303.7x^2-35.6x^3$	$y = 1036.5-910.1x+303.7x^2-35.6x^3$
Subject 3	$y = 1036.5-910.1x+303.7x^2-35.6x^3$	$y = 1036.5-910.1x+303.7x^2-35.6x^3$
Subject 4	$y = 1036.5-910.1x+303.7x^2-35.6x^3$	$y = 1036.5-910.1x+303.7x^2-35.6x^3$
Subject 5	$y = 1036.5-910.1x+303.7x^2-35.6x^3$	$y = 1036.5-910.1x+303.7x^2-35.6x^3$
1-Point**		
Subject 1	$y = 1036.5-910.1x+303.7x^2-35.6x^3$	$y = 1036.5-910.1x+303.7x^2-35.6x^3$
Subject 2	$y = 1036.5-910.1x+303.7x^2-35.6x^3$	$y = 1036.5-910.1x+303.7x^2-35.6x^3$
Subject 3	$y = 1036.5-910.1x+303.7x^2-35.6x^3$	$y = 1036.5-910.1x+303.7x^2-35.6x^3$
Subject 4	$y = 1036.5-910.1x+303.7x^2-35.6x^3$	$y = 1036.5-910.1x+303.7x^2-35.6x^3$
Subject 5	$y = 1036.5-910.1x+303.7x^2-35.6x^3$	$y = 1036.5-910.1x+303.7x^2-35.6x^3$
14-Point		
Subject 1	$y = 5886.5-5504.3x+1751.7x^2-187.5x^3$	$y = 896.1-678.5x+200.9x^2-22.0x^3$
Subject 2	$y = 4906.8-4764.4x+1582.8x^2-177.1x^3$	$y = 1703.5-1589.2x+529.1x^2-59.9x^3$
Subject 3	$y = 1678.5-1585.9x+541.9x^2-63.4x^3$	$y = 1865.0-1674.9x+540.5x^2-59.8x^3$
Subject 4	$y = 5557.9-5268.3x+1696.6x^2-183.3x^3$	$y = 2547.5-2316.1x+736.5x^2-79.4x^3$
Subject 5	$y = 3340.1-3182.2x+1048.5x^2-116.9x^3$	$y = 627.1-457.2x+141.4x^2-16.7x^3$

* Equations predicting forward inclination in Appendix II, Figure II-5 were converted to predict shoulder flexion (upward inclination) for the no calibration and 1-point calibration conditions.

** $x = x_1$+offset

where,
x = corrected voltage
x_1 = voltage recorded by inclinometers
offset = ave. x (at 90 deg. from Appendix II) - x in trial 1 (at 90 deg.)

TABLE III-2

Summary of the equations used to predict right and left knee flexion for each subject

(y = predicted knee flexion in deg., x = inclinometer voltage)

Calibration and Subject	Left KneeFlexion (deg.)	Right Knee Flexion (deg.)
None* and 1-Point**		
Subject 1	$y_u = -575.9+680.3x-244.3x^2+31.4x^3$ $y_l = -941.5+980.4x-324.4x^2+37.6x^3$	$y_u = -767.9+812.1x-268.2x^2+31.4x^3$ $y_l = -721.2+818.9x-285.8x^2+35.3x^3$
Subject 2	$y_u = -575.9+680.3x-244.3x^2+31.4x^3$ $y_l = -941.5+980.4x-324.4x^2+37.6x^3$	$y_u = -767.9+812.1x-268.2x^2+31.4x^3$ $y_l = -721.2+818.9x-285.8x^2+35.3x^3$
Subject 3	$y_u = -575.9+680.3x-244.3x^2+31.4x^3$ $y_l = -941.5+980.4x-324.4x^2+37.6x^3$	$y_u = -767.9+812.1x-268.2x^2+31.4x^3$ $y_l = -721.2+818.9x-285.8x^2+35.3x^3$
Subject 4	$y_u = -575.9+680.3x-244.3x^2+31.4x^3$ $y_l = -941.5+980.4x-324.4x^2+37.6x^3$	$y_u = -767.9+812.1x-268.2x^2+31.4x^3$ $y_l = -721.2+818.9x-285.8x^2+35.3x^3$
Subject 5	$y_u = -575.9+680.3x-244.3x^2+31.4x^3$ $y_l = -941.5+980.4x-324.4x^2+37.6x^3$	$y_u = -767.9+812.1x-268.2x^2+31.4x^3$ $y_l = -721.2+818.9x-285.8x^2+35.3x^3$
2-Point***		
Subject 1	$y = -10.2+55.6x_2$	$y = -34.1+74.3x_2$
Subject 2	$y = -11.4+61.2x_2$	$y = -33.4+56.1x_2$
Subject 3	$y = -20.5+51.7x_2$	$y = 1.8+48.2x_2$
Subject 4	$y = -38.0+69.8x_2$	$y = -110.9+65.5x_2$
Subject 5	$y = -65.5+112.2x_2$	$y = -30.1+108.7x_2$
11-Point***		
Subject 1	$y = -5.2+ 76.0x_2-40.3x_2^2-20.3x_2^3$	$y = 31.6+ 71.2x_2+8.2x_2^2-23.9x_2^3$
Subject 2	$y = -19.8+97.0x_2-47.9x_2^2-19.6x_2^3$	$y = 35.0+66.5x_2+3.2x_2^2-2.3x_2^3$
Subject 3	$y = -0.8+29.1x_2-83.3x_2^2-22.7x_2^3$	$y = -0.3+40.9x_2+13.1x_2^2+2.0x_2^3$
Subject 4	$y = -6.2+50.7x_2-100.1x_2^2-22.4x_2^3$	$y = -3.2+31.6x_2+45.3x_2^2-12.2x_2^3$
Subject 5	$y = -33.8-58.8x_2-30.8x_2^2-12.1x_2^3$	$y = -25.1-127.9x_2-52.7x_2^2+14.6x_2^3$

* Equations were used to predict forward inclination as in Appendix II, Figure II-5 for the no calibration and 1-point calibration conditions. Predicted knee flexion = the difference between the two angles of forward inclination (y_u= upper leg tilt, y_l = lower leg tilt).

** $x = x_1$+offset

where,

x = corrected voltage
x_1 = voltage recorded by inclinometers
offset = ave. x (at 90 deg. from Appendix II) - x in trial 1 (at 90 deg.)

*** x_2 = the difference in voltage between the upper and lower inclinometers

TABLE III-3

Summary of the equations used to predict trunk flexion for each subject

(y=predicted trunk flexion in deg., x= inclinometer voltage)

Calibration and Subject	Trunk Flexion (deg.)
None*	
Subject 1	$y = -938.8+814.1x-243.1x^2+25.6x^3$
Subject 2	$y = -938.8+814.1x-243.1x^2+25.6x^3$
Subject 3	$y = -938.8+814.1x-243.1x^2+25.6x^3$
Subject 4	$y = -938.8+814.1x-243.1x^2+25.6x^3$
Subject 5	$y = -938.8+814.1x-243.1x^2+25.6x^3$
2-Point	
Subject 1	$y = -228.6+71.4x$
Subject 2	$y = -204.2+67.2x$
Subject 3	$y = -200.6+65.1x$
Subject 4	$y = -137.3+48.7x$
Subject 5	$y = -146.0+53.1x$
3-Point	
Subject 1	$y = 315.4-226.9x+40.8x^2$
Subject 2	$y = 236.5-183.8x+35.6x^2$
Subject 3	$y = 149.7-122.4x+24.8x^2$
Subject 4	$y = -164.3+64.3x-2.2x^2$
Subject 5	$y = -13.6+26.0x-11.8x^2$
13-Point	
Subject 1	$y = -1844.7+-1676.3x-511.4x^2+52.8x^3$
Subject 2	$y = -887.6+-821.2x-258.6x^2+28.2x^3$
Subject 3	$y = -1053.0+986.2x-311.5x^2+633.6x^3$
Subject 4	$y = -2508.8+2187.6x-637.7x^2+62.9x^3$
Subject 5	$y = -560.0+515.2x-164.9x^2+19.0x^3$

* Equations predicting forward inclination in Appendix II, Figure II-5 were converted to predict shoulder flexion (upward inclination) for the no calibration condition.

TABLE III-4

Summary of the equations used to predict trunk lateral bending for each subject

(y =predicted lateral bending in deg., x = LMM measurement)

Calibration and Subject	Trunk Lateral Bending (deg.)
None*	
Subject 1	y=x
Subject 2	y=x
Subject 3	y=x
Subject 4	y=x
Subject 5	y=x
2-Point	
Subject 1	y = -1.9+1.3x
Subject 2	y = -1.1+1.1x
Subject 3	y = -0.6+1.4x
Subject 4	y = -7.6+1.4x
Subject 5	y = -4.2+1.2x
3-Point	
Subject 1	y = -0.9+1.3x
Subject 2	y = -1.5+1.1x
Subject 3	y = -1.8+1.4x
Subject 4	y = -6.4+1.4x
Subject 5	y = -4.4+1.2x
15-Point	
Subject 1	y = -0.4+1.3x
Subject 2	y = -1.9+1.1x
Subject 3	y = -2.2+1.3x
Subject 4	y = -5.0+1.3x
Subject 5	y = -6.1+1.2x

* LMM measurements used as a proxy for trunk posture.

TABLE III-5

Summary of the equations used to predict trunk torsion for each of the subjects

(y=predicted trunk torsion in deg., x= LMM measurement)

Calibration and Subject	Trunk Torsion Bending (deg.)
None*	
Subject 1	y=x
Subject 2	y=x
Subject 3	y=x
Subject 4	y=x
Subject 5	y=x
2-Point	
Subject 1	y = -1.9+1.0x
Subject 2	y = -2.3+0.8x
Subject 3	y = -3.0+1.2x
Subject 4	y = 4.4+1.0x
Subject 5	y = -5.6+1.1x
3-Point	
Subject 1	y = -1.6+1.0x
Subject 2	y = -3.1+0.8x
Subject 3	y = -2.8+1.2x
Subject 4	y = -3.9+1.0x
Subject 5	y = -5.2+1.1x
7-Point	
Subject 1	y = -0.5+0.7x
Subject 2	y = -4.9+0.4x
Subject 3	y = -4.5+0.8x
Subject 4	y = 3.6+0.8x
Subject 5	y = -6.0+0.8x

* LMM measurements used as a proxy for trunk posture.

APPENDIX IV

Electronic Postural Assessment System Prediction Equations Used in the Validity Study of Observational Assessments of Body Postures

TABLE IV-1

Summary of the equations used to predict shoulder, knee and trunk flexion for each of the subjects during simulated construction tasks

(y = predicted posture in deg., x = inclinometer voltage)

Shoulder Flexion No Calibration*	Left Shoulder Flexion (deg.)	Right Shoulder Flexion (deg.)
Subject 1-Subject 5	$y = 1036.5-910.1x+303.7x^2-35.6x^3$	$y = 1036.5-910.1x+303.7x^2-35.6x^3$

Knee Flexion 2 Point**	Left Knee Flexion (deg.)	Right Knee Flexion (deg.)
Subject 1	$y = -134.0+208.3x$	$y = -54.4+297.6x$
Subject 2	$y = -47.8+112.6x$	$y = -6.5+135.1x$
Subject 3	$y = -66.1+167.8x$	$y = -17.6+147.9x$
Subject 4	$y = -98.8+164.5x$	$y = -40.4+252.5x$
Subject 5	$y = -31.0+93.3x$	$y = -41.9+87.7x$

Trunk Flexion No Calibration*	Trunk Flexion (deg.)
Subject 1-Subject 5	$y = -938.8+814.1x-243.1x^2+25.6x^3$

* Equations predicting forward inclination in Appendix II, Figure 43 were converted to predict shoulder flexion (upward inclination) for the no calibration and 1-point calibration conditions.

** x = the difference in voltage between the upper and lower inclinometers

TABLE IV-2

Summary of the equations used to predict trunk lateral bending and torsion for each of the subjects during simulated construction tasks

(y = predicted shoulder flexion in deg., x = LMM measurement)

Trunk Lateral Bending 2-Point	Trunk Lateral Bending (deg.)
Subject 1	y = -11.7+2.1x
Subject 2	y = -9.5+1.9x
Subject 3	y = -8.0+1.9x
Subject 4	y = -15.1+2.0x
Subject 5	y = -3.3+1.2x
Trunk Torsion 3-Point	Trunk Lateral Bending (deg.)
Subject 1	y = -0.4+1.2x
Subject 2	y = -1.1+1.1x
Subject 3	y = 1.4+1.1x
Subject 4	y = -6.4+1.4x
Subject 5	y = -3.7+1.6x

APPENDIX V

Use of the Bootstrap to Evaluate the Reliability of Different Assessment Periods for Exposures of Differing Frequency and Variability in 3 Highway Construction Operations

TABLE V-1.

Summary of the data used in the bootstrapping of concrete-reinforcement job tasks

Frequency	Task	Exposure	2 Day Variability (% time on each day)	Average Obs./Day	Minimum Obs./Day	Total Workers	Total Days
High	Ground-level Rebar Construction	Load Handling	High (61.7, 54.8)	93	47	17	6
	Ground-level Rebar Construction	Trunk Flexion	Low (51.1, 49.6)	94	47	17	6
Medium	Preparation Work	MMH	High (35.0, 10.0)	90	49	16	6
	Preparation Work	Trunk Lateral Bending or Torsion	Low (17.0, 17.1)	90	49	16	6
Low	Vertical Rebar Construction	Arm(s) above Shoulders	High (0.0, 13.9)	99	44	15	5
	Ground-level Rebar Construction	Power-tool Use	Low (0.0, 0.9)	90	46	17	6

TABLE V-2

Summary of the data used in the bootstrapping of jacking-pit-construction job tasks

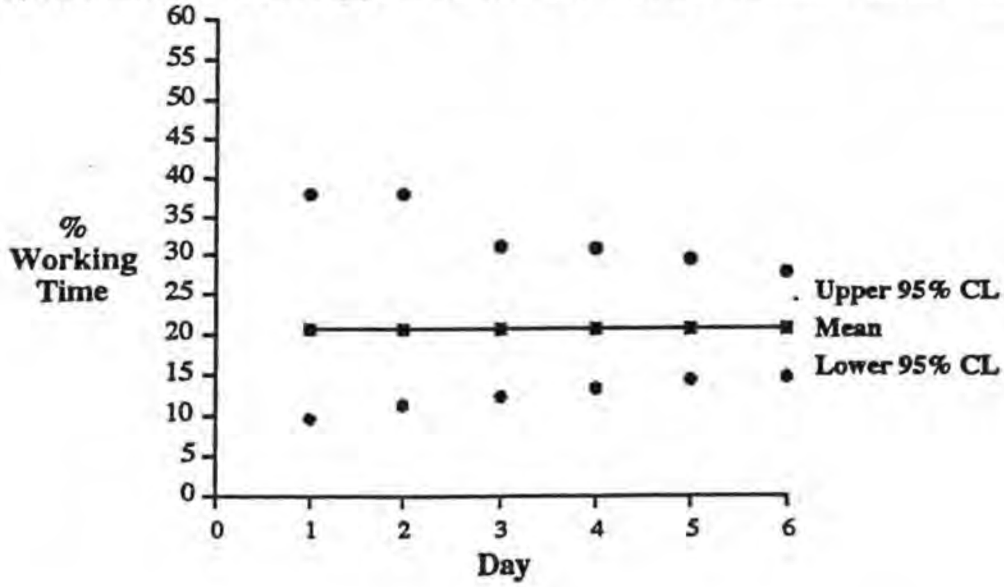
Frequency	Task	Exposure	2 Day Variability (% time on each day)	Average Obs./Day	Minimum Obs./Day	Total Workers	Total Days
High	Manual Excavation	Kneeling, Squatting or Leg Bending	High (12.7, 61.2)	139	40	10	10
	Pit Wall Construction	Trunk Flexion	Low (31.1, 40.9)	74	43	9	7
Medium	Misc. Work	Trunk Non-neutral	High (33.9, 2.2)	72	43	10	7
	Manual Excavation	Power-tool Use	Low (8.5, 7.5)	139	40	10	10
Low	Pit Wall Construction	MMH	High (11.1, 3.4)	70	45	9	7
	Top Work	Trunk Lateral Bending or Torsion	Low (4.7, 5.3)	115	57	7	6

TABLE V-3

Summary of the data used in the bootstrapping of the form-construction job tasks

Frequency	Task	Exposure	2 Day Variability (% time on each day)	Average Obs./Day	Minimum Obs./Day	Total Workers	Total Days
High	Form Erection	Non-neutral Trunk	High (56.1, 67.1)	67	49	7	4
	Form Erection	Trunk Flexion	Low (31.6, 32.9)	67	49	7	4
Medium	Form Erection	Kneeling, Squatting or Leg Bending	High (17.5, 10.0)	67	49	7	4
	Form Erection	MMH	Low (14.0, 14.3)	67	49	7	4
Low	Form Erection	Hand-tool Use	High (12.3, 7.1)	67	49	7	4
	Form Erection	Load Handling	Low (8.0, 3.3)	67	49	7	4

a) Load handing > 44 N during ground-level rebar construction (mean # obs = 93, min # obs = 47)



b) Trunk flexion during ground-level rebar construction (mean # obs = 94, min # obs = 47)

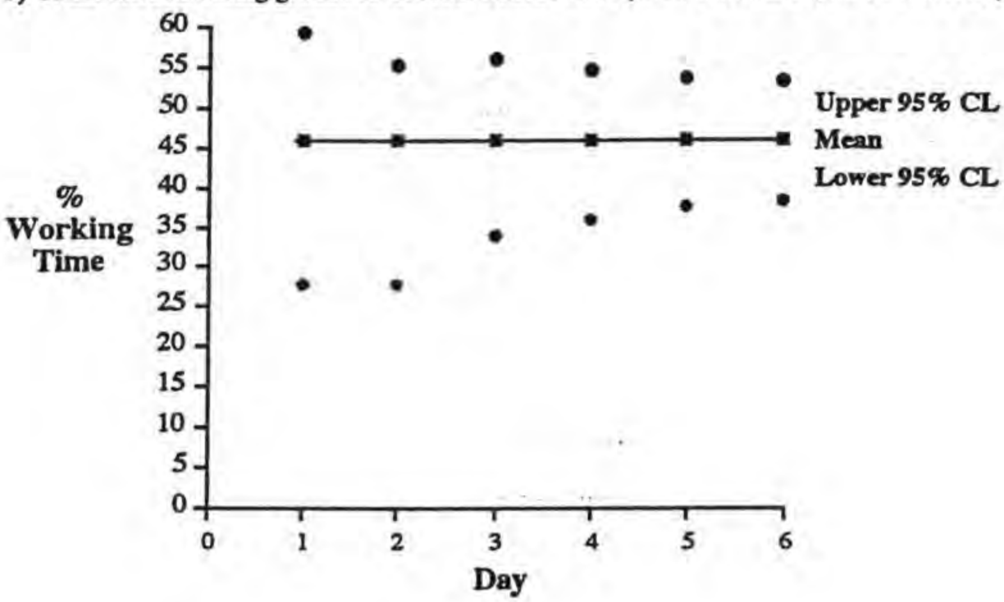
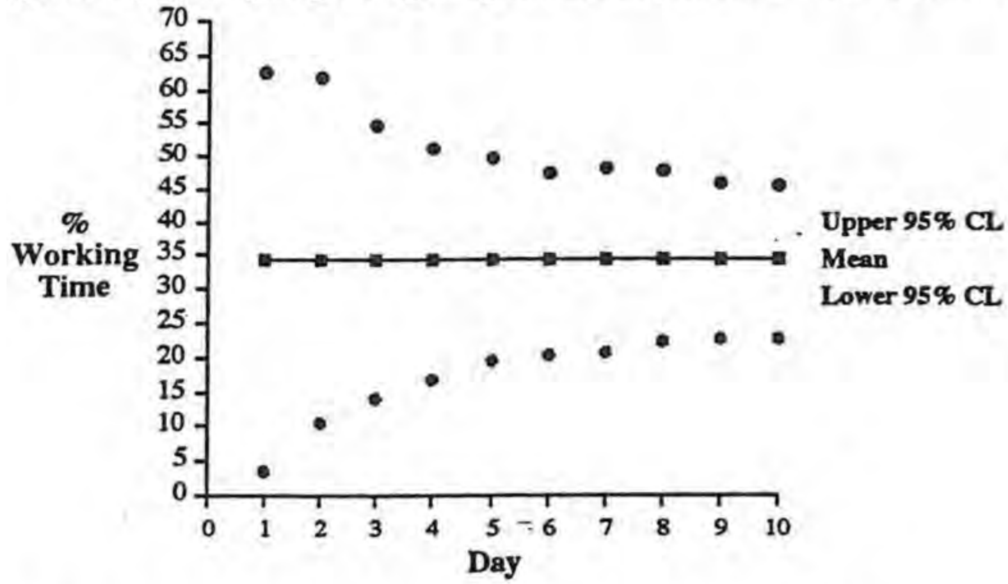


Figure V-1. Mean exposure estimates (% working time) during the concrete-reinforcement operation using the data generated with the bootstrap based on 1000 sets: a) high exposure frequency, high exposure variance, b) high exposure frequency, low exposure variance during the first 2 days of observation.

a) Kneeling, squatting or leg bending during manual excavation (mean # obs = 139, min # obs = 40)



b) Trunk flexion during pit-wall construction (mean # obs = 74, min # obs = 43)

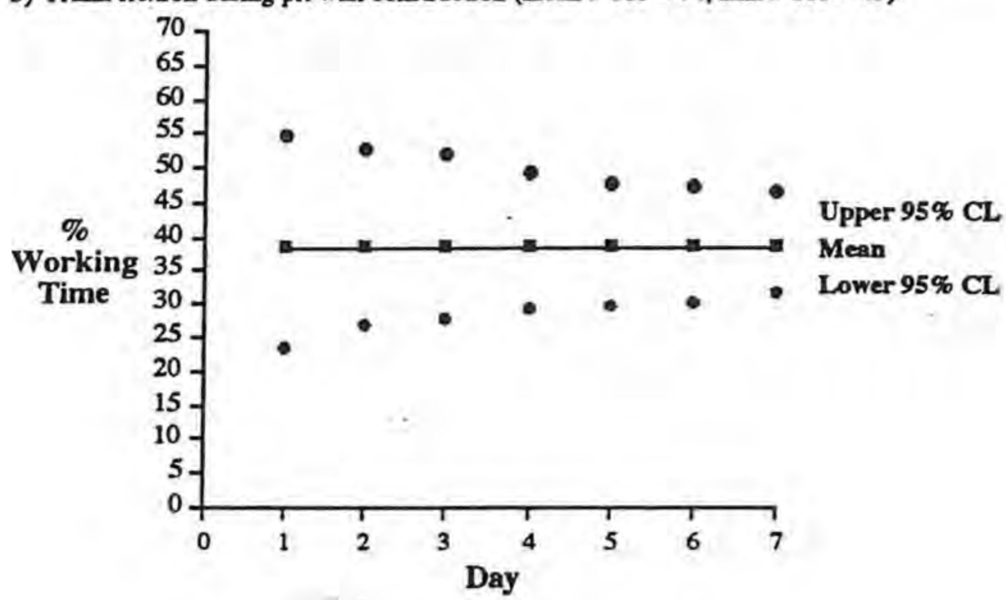
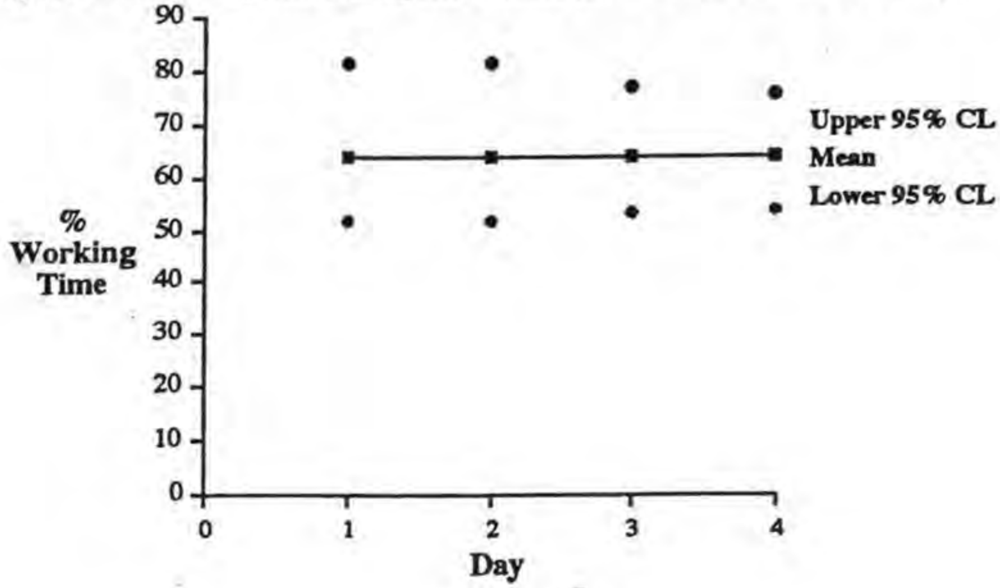


Figure V-2. Mean exposure estimates (% working time) during the jacking-pit construction operation using the data generated with the bootstrap based on 1000 sets: a) high exposure frequency, high exposure variance, b) high exposure frequency, low exposure variance during the first 2 days of observation.

a) Non-neutral trunk postures during form erection (mean # obs = 67, min # obs = 49)



b) Trunk flexion during form erection (mean # obs = 67, min # obs = 49)

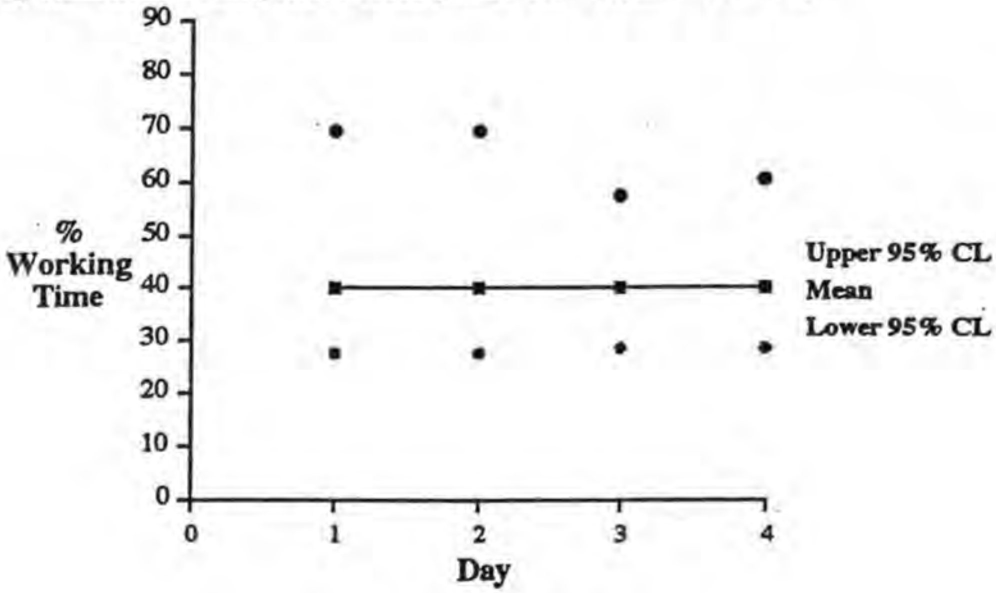
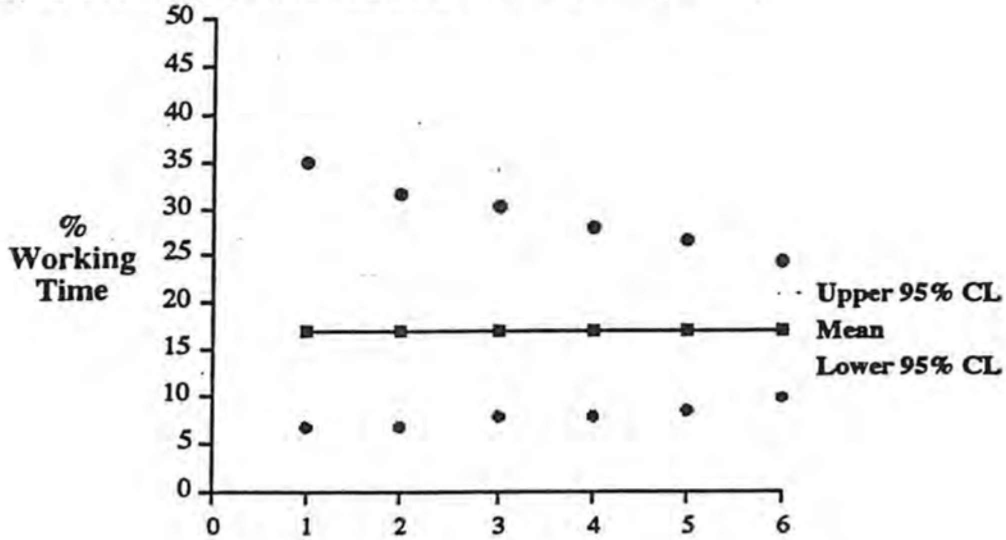


Figure V-3. Mean exposure estimates (% working time) during the form-construction operation using the data generated with the bootstrap based on 1000 sets: a) high exposure frequency, high exposure variance, b) high exposure frequency, low exposure variance during the first 2 days of observation.

a) MMH during preparation work (mean # obs = 90, min # obs = 49)



b) Trunk lateral bending or torsion during preparation work (mean # obs = 90 , min # obs = 49)

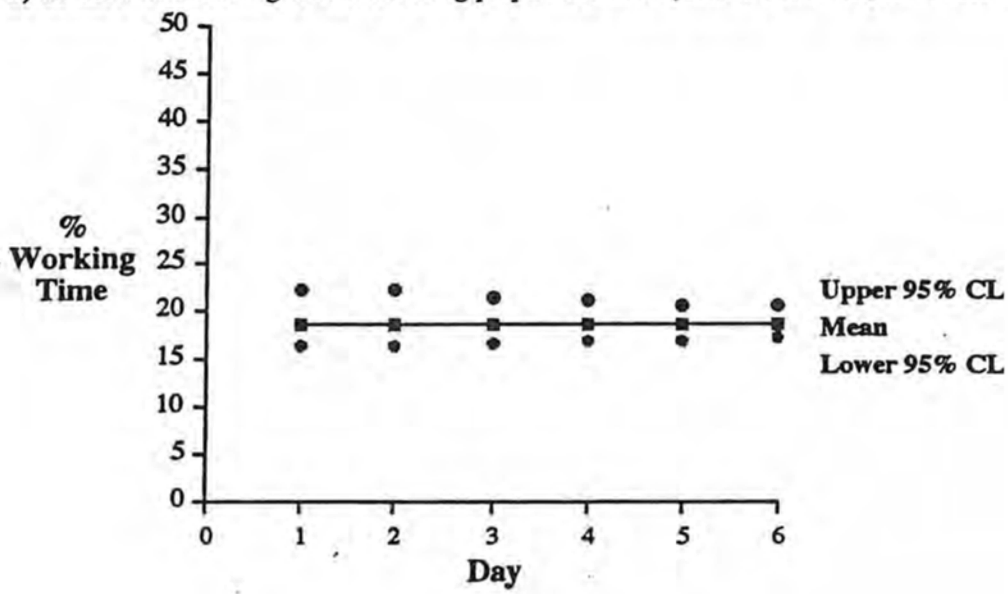
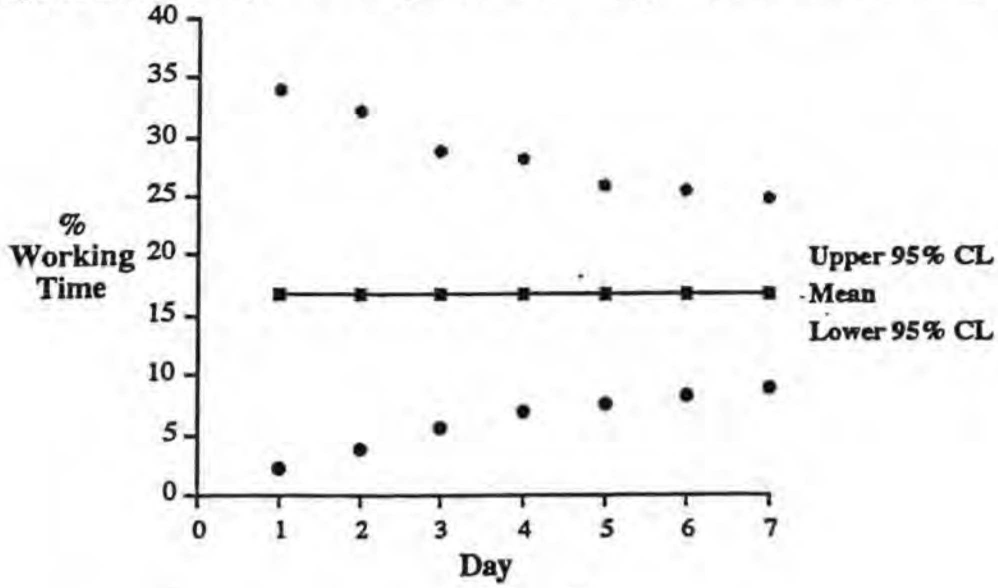


Figure V-4. Mean exposure estimates (% working time) during the concrete-reinforcement operation using the data generated with the bootstrap based on 1000 sets: a) medium exposure frequency, high exposure variance, b) medium exposure frequency, low exposure variance during the first 2 days of observation.

a) Non-neutral trunk postures during miscellaneous work (mean # obs = 72, min # obs = 43)



b) Power tool use during manual excavation (mean # obs = 139, min # obs = 40)

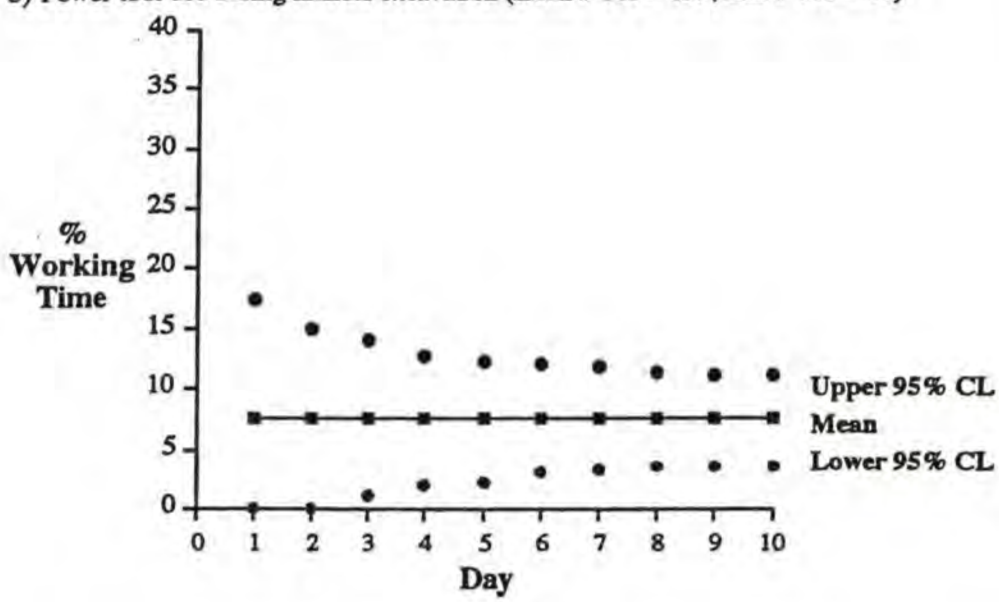
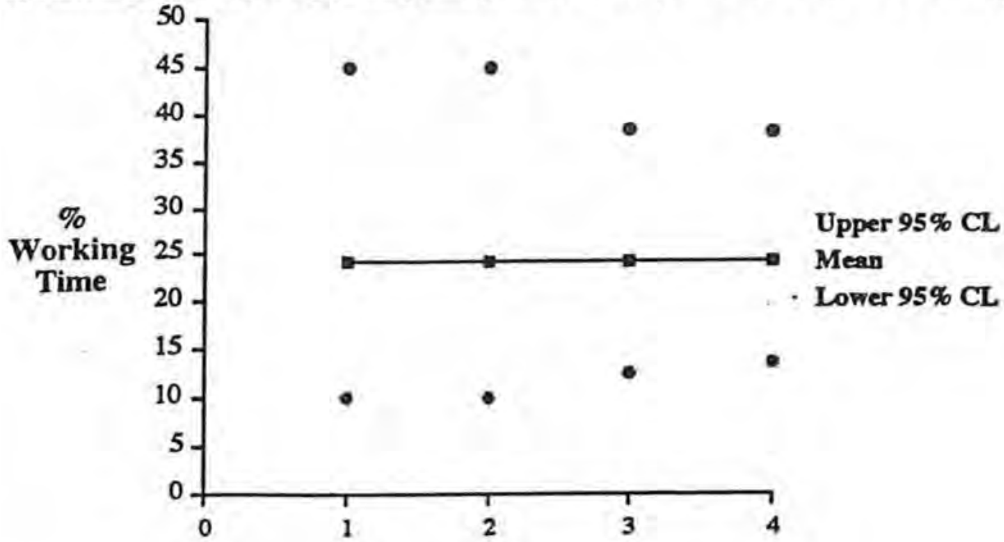


Figure V-5. Mean exposure estimates (% working time) during the jacking-pit construction operation using the data generated with the bootstrap based on 1000 sets: a) medium exposure frequency, high exposure variance, b) medium exposure frequency, low exposure variance during the first 2 days of observation.

a) Kneeling, squatting or leg bending during form erection (mean # obs = 67, min # obs = 49)



b) MMH during form erection (mean # obs = 67, min # obs = 49)

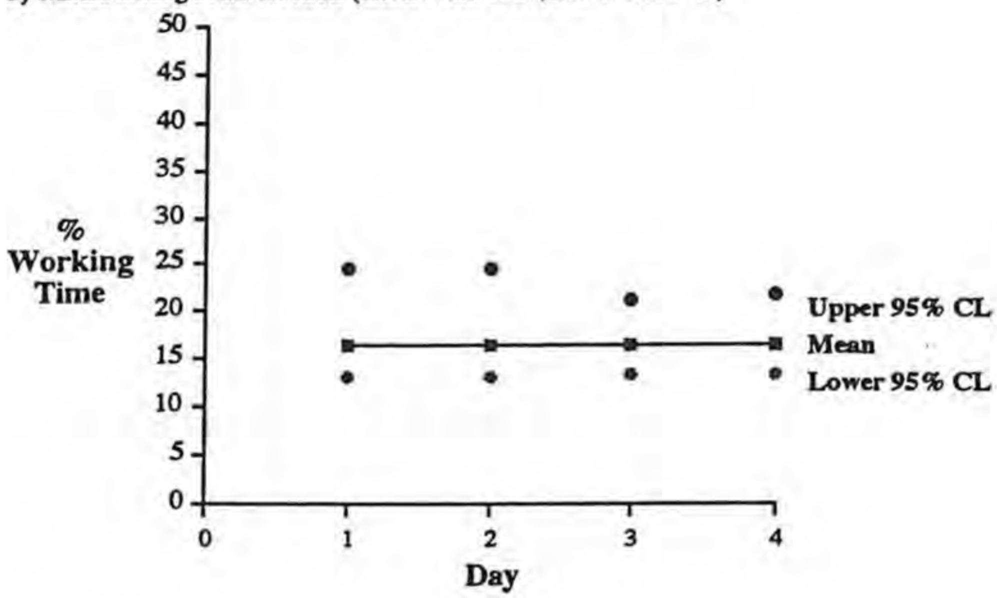
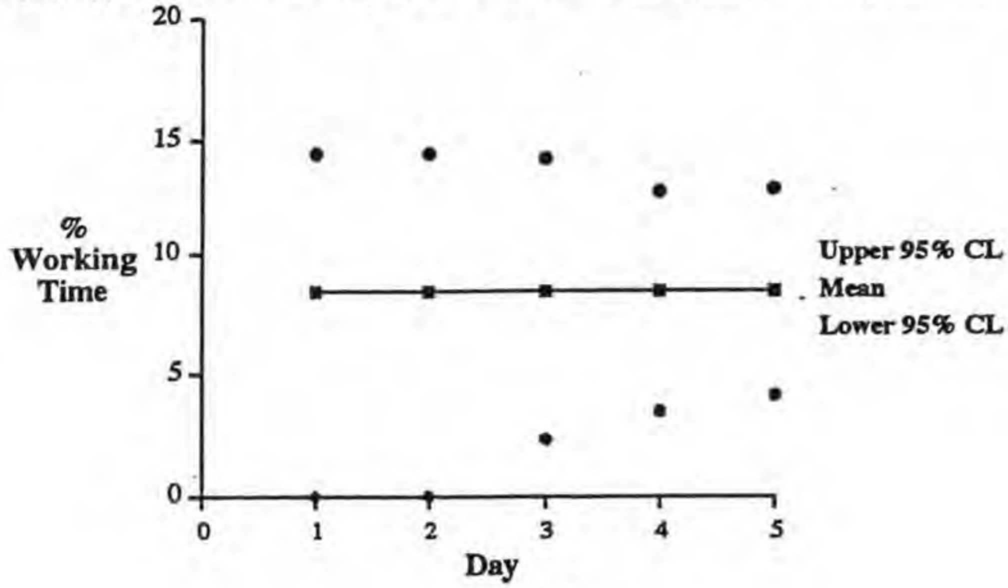


Figure V-6. Mean exposure estimates (% working time) during the form-construction operation using the data generated with the bootstrap based on 1000 sets: a) medium exposure frequency, high exposure variance, b) medium exposure frequency, low exposure variance during the first 2 days of observation.

a) Arm(s) above shoulders during vertical rebar construction (mean # obs = 99, min # obs = 44)



b) Power tool use during ground-level rebar construction (mean # obs = 90, min # obs = 46)

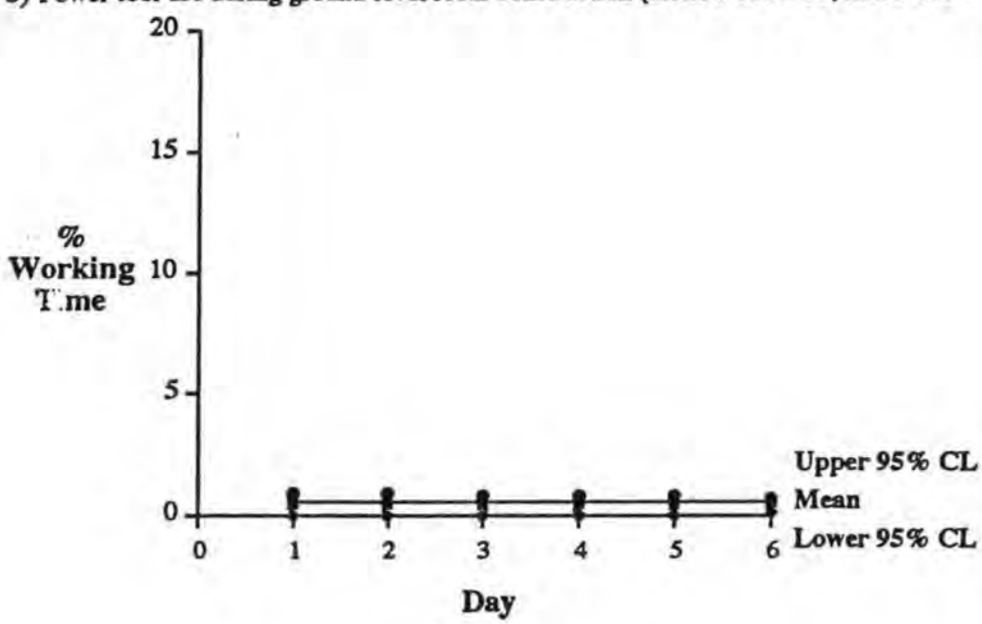
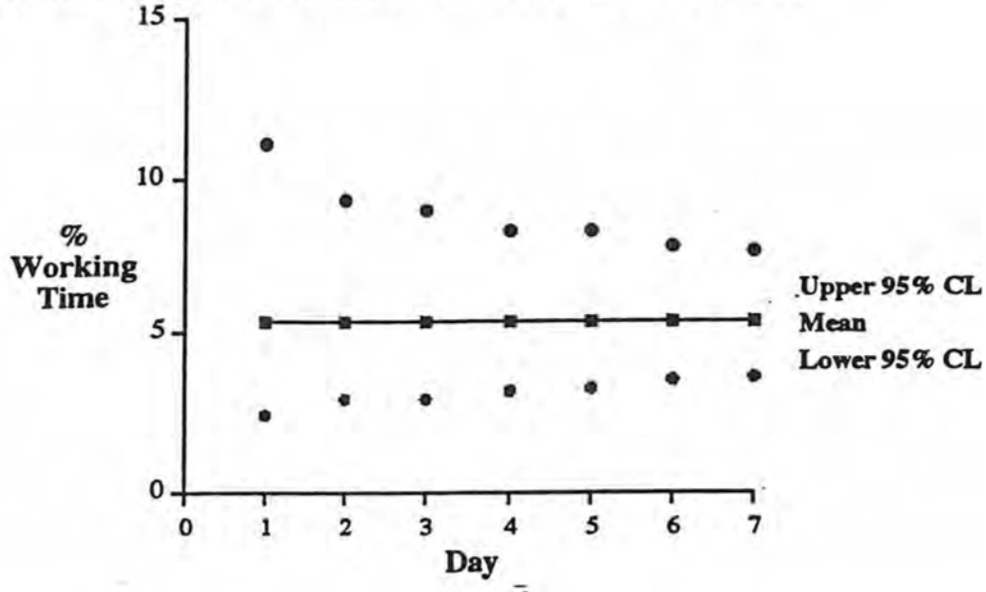


Figure V-7. Mean exposure estimates (% working time) during the concrete-reinforcement operation using the data generated with the bootstrap based on 1000 sets: a) low exposure frequency, high exposure variance, b) low exposure frequency, low exposure variance during the first 2 days of observation.

a) MMH during pit-wall construction (mean # obs = 70, min # obs = 45)



b) Trunk lateral bending or torsion during top work (mean # obs =115, min # obs = 57)

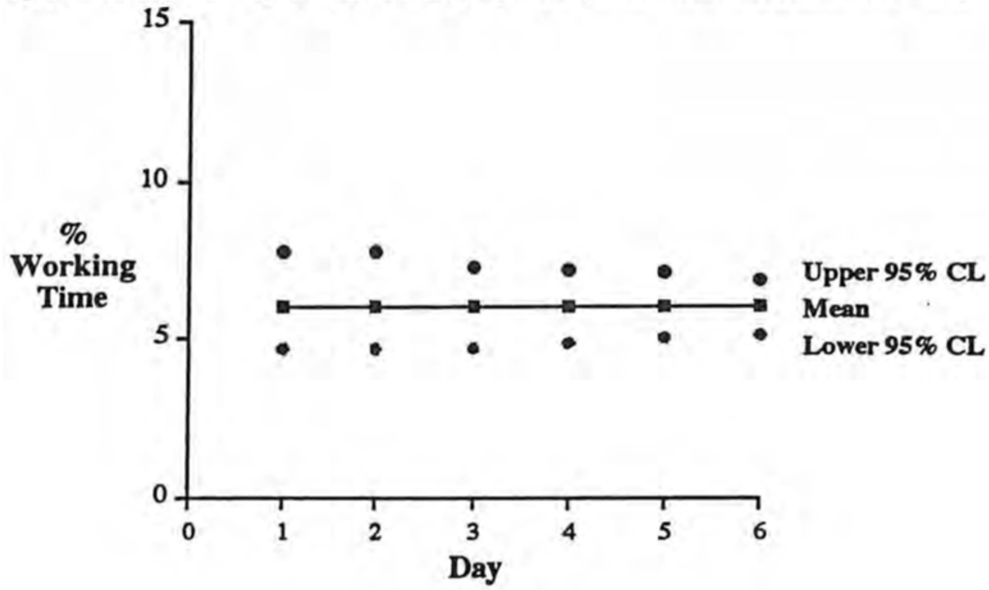
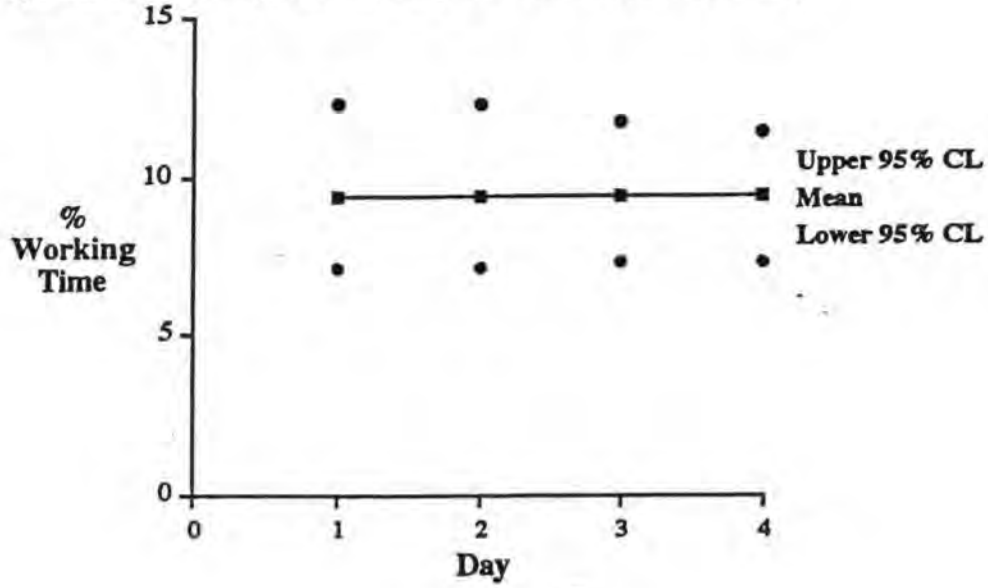


Figure V-8. Mean exposure estimates (% working time) during the jacking-pit construction operation using the data generated with the bootstrap based on 1000 sets: a) low exposure frequency, high exposure variance, b) low exposure frequency, low exposure variance during the first 2 days of observation.

a) Hand-tool use during form erection (mean # obs = 67, min # obs = 49)



b) Load handling ≥ 6.8 during form erection (mean # obs = 67, min # obs = 49)

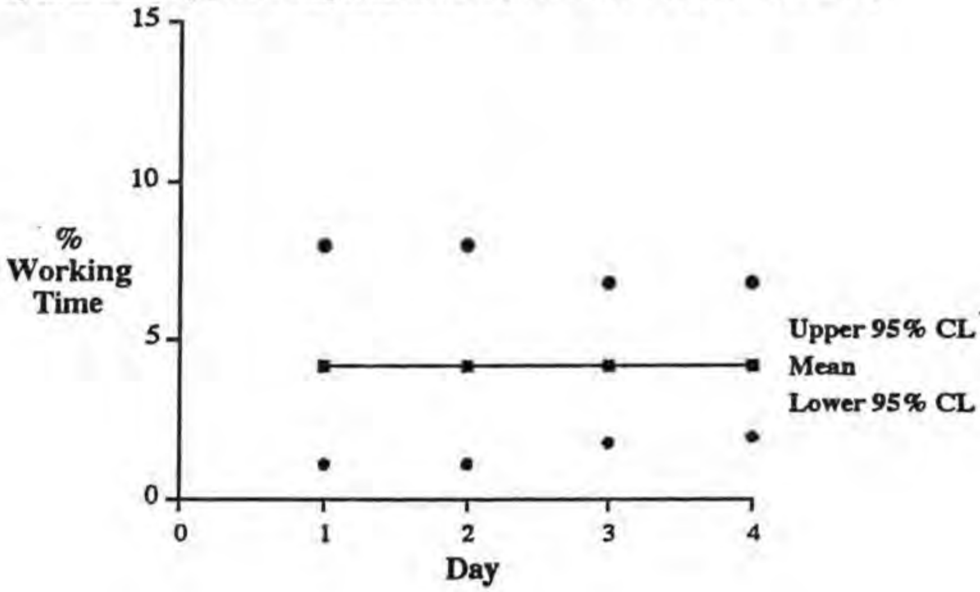


Figure V-9. Mean exposure estimates (% working time) during the form-construction operation using the data generated with the bootstrap based on 1000 sets: a) low exposure frequency, high exposure variance, b) low exposure frequency, low exposure variance during the first 2 days of observation.

BIOGRAPHICAL SKETCH OF AUTHOR

Victor Leo Paquet III was born on February 14, 1969 in Malden, MA. As an engineering psychology major, he received a B.S. degree from Tufts University in May, 1991. He then studied human factors engineering and safety while enrolled in the Industrial and System Engineering Department at Virginia Polytechnic Institute and State University and received a M.S. degree from this department in 1995. In 1993, he began study at the University of Massachusetts Lowell where he now pursues a Sc.D. degree in Work Environment. While studying in this department, Victor has worked as a research assistant for the Construction Occupational Health Project, part of a national research effort aimed at the prevention of injury and illness among construction workers. His current research interests include the evaluation of controls intended to reduce work-related musculoskeletal injury, the development and evaluation of hazard surveillance tools used by workers and practitioners, musculoskeletal epidemiology and organizational issues that affect worker health and safety.