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Measuring trunk motions in industry: variability due to task factors, individual differences, and the amount of data collected

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The focus of this study was to determine the amount of data needed to ensure sufficient accuracy in estimating mean trunk motions of employees performing industrial manual materials handling tasks. Over 450 tasks were selected, in which the load weight and the vertical start and destination heights of the activity remained constant throughout the task. Data were collected as employees did their work at the job site, using the Lumbar Motion Monitor. Variance components were estimated in a hierarchical design and used to compute standard errors of mean trunk kinematic measures. These analyses found task-to-task variation to be much larger than the variability due to either multiple employees performing the same task or to repetitive movements within a task. Also, it was found that no significant reduction in the standard errors occurred when data were gathered for more than three employees and three repetitions of each task by an employee. This study indicates that the vast majority of variability in mean trunk motions is accounted for by the design of work tasks, and variations due to repeated cycles of a task or to employees are rather minor. It is also important as a basis for future work on modelling low-back disorder risk based on a job's trunk kinematic measures.

1. Introduction

The question of how much information is needed to adequately represent the variability in a job task is a basic experimental design issue. Too few data may not fully characterize a task, and, from a practical standpoint, gathering too much data can drain valuable time and resources. Under laboratory conditions, how much variability to expect is typically known based upon pilot studies. However, the need to collect data outside the laboratory, in more realistic but less controlled settings, is far more difficult to characterize and is especially problematic for the industrial ergonomics discipline. This is because, from a biomechanical perspective, the activities and movements of employees doing their actual jobs can differ dramatically from when these actions are simulated in highly controlled, laboratory settings. The nature of industrial data collection may require other considerations in addition to

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those involved with more traditional issues of variability and sample sizes in experimental designs. For example, with manual materials handling (MMH) tasks, often only a few employees have the expertise to perform a job of interest. In a laboratory, the researcher can design a study and recruit as many subjects as needed. In industrial settings, these issues are dictated by the work environment. Unfortunately, the literature provides little guidance regarding the amount of industrial data that are 'enough' to represent a task.

Collecting data in industrial settings can be time-consuming and expensive for investigators, and the need to study employees as they do their work can sometimes be disruptive to the production process. Therefore, it is important to determine how much data must be gathered to assure that the tasks performed are accurately represented. For this reason, the need exists to understand the variability of industrial data and determine the amount that should be gathered to accurately depict the requirements of a job, in a pragmatic fashion.

A research area where these issues have become apparent is the assessment of musculoskeletal injury risk, which requires surveillance of industrial work tasks. For example, Marras *et al.* (1993, 1995) studied over 400 MMH activities and collected data as employees performed their jobs. They developed a model of low-back disorder (LBD) risk, based on actual workplace and trunk kinematic factors. Marras and Schoenmarklin (1993) conducted a similar industrial-based study of the wrist joint. These types of results are more likely to reflect the true nature of manual work, but they do not provide details regarding the appropriate volume of data necessary to accurately characterize the specific job task.

An implication of conducting industrial-based studies is their potential high degree of variability. This is certainly the case for MMH tasks. Production processes and the nature of work performed within an individual facility or across multiple facilities can vary greatly, as one would expect. For example, installing doors, tyres, or windshields onto a vehicle in an automobile assembly plant can be similar in their nature (i.e. work rate), but the load weights and handling requirements can be quite different. Further, a specific task (e.g. loading a tyre onto an automobile) can vary greatly from one assembly plant to another. Marras *et al.* (1995) studied trunk kinematic variability in the three planes of motion for a wide variety of MMH tasks and compared between-job variability to within-job variability for these kinematic parameters. For the most part, these researchers collected large amounts of data for each task. They found that, in a majority of the cases, most of the variation was a result of differences from job to job rather than to repetition variability within the jobs. They concluded that trunk motions were, thus, dictated more by the design of the jobs and that repeatedly doing the work resulted in fairly similar motions.

Variability also can occur across employees performing the same task. This may be the result of work experience, physical differences (e.g. size, strength) between employees, or individual preferences for how the work is performed. This issue also needs to be considered in the determination of appropriate data collection amounts.

In the assessment of a task's risk of musculoskeletal injury, trunk motion variables need to be averaged over a number of employees performing the task as well as over several repetitions of the task by each employee. Thus, the focus of this study was on accuracy of estimation of mean kinematic measures for a task, where the mean is taken over employees and repetitions of the tasks by employees. This issue of understanding and minimizing the variability in a task's mean trunk motion is of growing concern, since it has been reported in the literature that the risk of LBD is associated more with dynamic tasks than when measuring similar activities statically. For example, Magora (1973) concluded that twisted and lateral positions of the trunk were significant risk factors for LBD only when they were combined with 'quick' or sudden movements. Data from Bigos *et al.* (1986) implied that reports of LBD were more numerous for dynamic tasks than for static tasks, and Punnet et al. (1991) reported that postural stress was more related to dynamic than to static activities.

Marras *et al.* (1993, 1995) also determined the importance of trunk kinematics in assessing LBD risk, by studying over 100 workplace and trunk kinematic variables in more than 400 MMH jobs. They used a logistic regression model and found that five factors best distinguished between low- and high-risk jobs. These included two workplace factors—maximum external moment and lifting rate (across all tasks comprising a job), and three trunk kinematic factors—maximum sagittal flexion position, average twisting velocity, and maximum lateral velocity. Using this model, they calculated the odds of determining the probability that a job would be classified as high-risk and found it to be very high—10.7 times better than chance. Also, the multivariate nature of this model indicates that its predictive ability is much better than for any single variable individually.

In this study, the questions to be answered were, 'How many employees and how many repetitions per employee should be measured to adequately describe the risk parameters of the task being studied?' For the purposes of discussion, consider a single variable, say maximum sagittal flexion. The goal was to reduce the variability about the mean of the maximum sagittal flexion variable of a particular task over a population of employees and repetitions, subject to practical constraints. Of great interest, for instance, was the question of whether the labour involved in such a study could be reduced by sampling fewer employees or taking fewer measurements per employee.

2. Method

2.1. *Data source*

The data used for these analyses were collected across 61 industrial manufacturing facilities in the Midwest, over a time period of roughly 10 years. The initial purpose for gathering these data was to determine the dynamic trunk motions of employees performing high- and low-risk manual materials handling jobs (Marras *et al.* 1993, 1995). Data were gathered, for example, in automobile and truck assembly, food processing, rubber and plastics, printing and paper, glass production, machined products, and electronic equipment manufacturing plants. Some jobs were force-paced and occurred along an assembly line, others involved working with output from individual machines, while still others allowed for more self-paced operations. Also, the low-back strain rate for these jobs ranged from 0 to 133 incidents per 100 person-years of exposure. However, all jobs were repetitive in nature and involved some level of MMH.

2.2. *Subjects*

A total of 567 different employees were included in this database. Descriptive statistics for their age, weight, and anthropometric characteristics (measured in accordance with Webb Associates 1978) are shown in table 1. As this table shows, the samples represented a wide range of employee ages and body sizes. The database was comprised of 422 males (nearly 75% of the sample) and 145 females (slightly

Table 1. Ranges of anthropometric data of employees monitored for this study.

Variable	Units	Mean	SD	Minimum	Maximum
Age	years	38.5	10.1	19.0	63.0
Height	cm	174.3	9.2	147.9	196.5
Weight	N	784.0	168.3	400.3	1,601.4
Shoulder height	cm	144.3	8.3	121.6	168.5
Elbow height	cm	109.1	6.3	88.3	125.5
Upper arm length	cm	35.5	2.7	28.4	46.0
Lower arm length	cm	47.3	3.5	29.3	55.2
Trunk length	cm	54.6	4.3	40.7	66.4
Trunk breadth	cm	31.0	4.2	20.0	51.4
Trunk depth	cm	24.4	4.8	13.9	44.6
Trunk circumference	cm	92.6	14.1	58.0	149.0
Upper leg length	cm	45.6	4.2	34.5	57.3
Lower leg length	cm	49.1	3.8	33.0	66.1
Body mass index	–	26.2	4.3	16.5	48.1

more than 25% of the sample). Employees averaged 13.0 years (SD = 9.0 years) with their company and 4.0 years (SD = 5.1 years) working at the job in which they were monitored.

2.3. *Apparatus*

Trunk motions were gathered using the Lumbar Motion Monitor (LMM), which has been described and validated elsewhere (Marras *et al.* 1992) and is shown in figure 1. The LMM is essentially a tri-axial electrogoniometer that acts as an exoskeleton of the lumbar spine. It attaches to individuals directly in line with their spines, via harnesses at the pelvis and thorax and measures the instantaneous position, velocity and acceleration of the trunk. Figure 2 shows the LMM being worn by an employee while performing a repetitive MMH task. It was believed that wearing this apparatus did not significantly limit or influence the trunk motions of those who were monitored because of the light weight of the LMM, the design of the harness, and the short time in which they were worn (usually 20 min or less). Another variable collected, the maximum external moment, was derived by weighing the loads handled with a scale and measuring the horizontal distance from the employee's L_5/S_1 joint to the centre of the hands as the load was moved, using a tape measure.

2.4. *Data analysis*

The physical workplace arrangements of the tasks monitored varied greatly. With many tasks, the nature of the work was such that objects of different weights were handled or loads were moved to and from various vertical locations. These workplace features complicated the objectives of this study and added to the variability in the data. One goal of this study was to determine variability in how the work was performed due to task features and the fact that those features changed *within* some tasks masks the true nature of this variability. As a result, further analyses were performed only on tasks that did not vary on specific workplace parameters. That is, only the tasks that required handling objects of constant weight, that were lifted from the same vertical starting position, and that were placed at the same vertical destination height were included in further calculations. An example of

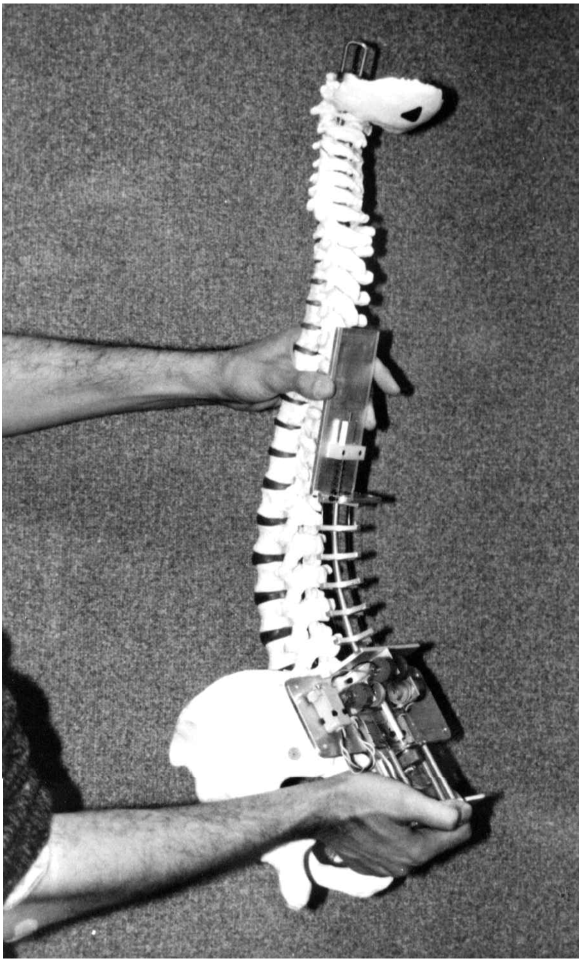

Figure 1. The Lumbar Motion Monitor (LMM).

a task that would fit this profile is a repetitive assembly operation, in which identical parts are retrieved from a bin at the same location and placed on an assembly line at a constant height. As shown in table 2, this reduced the total number of task repetitions in the entire database (8707) to a subset of 3246 repetitions (37.3% of the total), the number of tasks from 1048 to 478 (45.6% of the total), and the number of employees monitored across these tasks from 1280 to 520 (40.6% of the total). In the original database, the mean number of repetitions collected per task was slightly more than eight; this number was reduced in the subset database to slightly less than seven repetitions per task.

Of interest is the question of whether the effort involved in on-site data collection could be reduced significantly by sampling fewer employees doing a task or taking fewer measurements per employee, while still maintaining an optimal degree of accuracy. The method of variance components modelling was used, as in Marras *et al.* (1995), but rather than devising a two-stage model with job and repetition as factors, a three-stage model was used, with job task, employee, and repetition as

Figure 2. The LMM, as worn on an employee performing a manual materials handling task.

Table 2. Composition of the industrial database in which trunk motions were gathered.

	Entire database	Database subset
Total repetitions of work across all tasks and employees monitored	8707	3246
Total number of tasks monitored	1048	478
Mean number of repetitions monitored per task	8.3	6.8
Total number of employees monitored across all tasks	1280	520

factors. This finer detail was required for this analysis, whereas it was not needed in the study by Marras *et al.* (1995). In particular, the variance due to employee was of prime interest in this study. If employee variance is largely relative due to repetition, then taking more employees rather than more repetitions per employee would be the way to reduce variance of the overall estimated mean.

The task factor was needed in this study to take advantage of the many tasks represented in the database. The main interest was not in task-to-task variation; however, use of the task factor in the model enabled information to be pooled on employees and repetitions across all the tasks, thus giving more accurate estimates of the components of variance of interest.

In this study, the number of tasks of interest was 478, the number of employees monitored per task ranged from one to five, and the number of times an employee performed a task ranged from two to 37. There were 3246 observations altogether. Thus, this was a case of severely imbalanced data. The restricted maximum likelihood method (REML) of estimation of Patterson and Thompson (1971), which was described in Hocking (1985: 244 – 249) was used. In this method, the likelihood function based on the normal distribution is factored into two parts, one depending only on the parameters of interest, those characterizing the variances components (called ø). This factor is maximized with respect to ø, and the result is used as the estimator of ø. The maximization of the second factor with this estimation of ø fixed then yields an estimate of the remaining parameters. This method is related to both maximum likelihood and the method of moments, while generally requiring less computation.

The imbalance in this database, in terms of numbers of employees and repetitions collected per task, means that the analysis was run on the full database and on a balanced subset. The balanced subset consisted of tasks in which equal numbers of employees and repetitions were taken. This served as a check that the imbalance did not distort the estimates. Results from these two sets of data were almost identical. Also, the asymptotic covariance matrices were checked for all variables and, in every case, the asymptotic standard error of the estimate did not exceed 10% of the value of the variance component. This justified the use of these estimates as precise values.

Equation 1 was developed to compute the standard error (SE) of means of variables for each dependent variable. The format of this equation gives insight to the combination of numbers of employees or repetitions that will most reduce the SE about a specific variable. For example, variables having large error variances within repetitions by an employee performing a task or within an employee doing a task will benefit by both the addition of more employees *and* repetitions during trunk motion data collection. This will result in a reduction of the variable's SE. Also, this equation shows that, if a variable has a small error variance, then adding more repetitions of a task will do little to further reduce the SE. Equation 1 can be used as a guide, along with the coefficients in table 3, to determine, for a specific variable, the focus of trunk kinematic data collection that will produce the greatest reduction in a variable's SE.

$$\mathrm{SE} = \frac{\text{Variance (Error)}}{(\text{No. of employees}) \times (\text{No. of repetitions})} + \frac{\text{Variance (Employees (Task))}}{(\text{No. of employees})} \qquad (1)$$

3. Results

Use of the variance components analysis determined task, employee, and repetition variance components estimators for each of the trunk motion variables produced using the LMM. This procedure was also used to derive estimates of variance components for the maximum external moment variable. All are shown in table 3. It was of most interest to determine the effects on accuracy of the SE estimates due to the inclusion of data from additional employees or to additional repetitions within a task. The impact of the accuracy of these estimates due to adding more *tasks* was not a priority.

The estimators of employee and error components of variance in table 3 were derived using the REML estimation procedure. The task factor also was included in the model since it was a significant component of variance; however, this component was not of interest for our purpose, and the estimates are not reported here.

Figure 3 shows the estimated SEs of task mean values for four variables, as a function of number of employees and number of repetitions per employee for each task. The estimated SEs were derived from equation 1, using the variance components estimates in table 3. The four variables for which this is shown here are maximum external moment, maximum sagittal flexion position, maximum lateral

Table 3. Variance estimators for all trunk kinematic variables, analysed on the database subset.

Variable	Units	Variance (Employee (Task))	Variance (Error)
Lateral plane			
Maximum left bending position	°	7.58	5.50
Maximum right bending position	°	8.24	5.27
Maximum range of motion	°	7.04	8.56
Average velocity	°/s	5.78	1.49
Maximum velocity	°/s	45.28	36.99
Maximum acceleration	°/s^2	1350.98	2235.61
Sagittal plane			
Maximum extension position	°	24.08	5.84
Maximum flexion position	°	38.36	15.15
Maximum range of motion	°	10.09	16.41
Average velocity	°/s	1.82	1.84
Maximum velocity	°/s	15.15	55.14
Maximum acceleration	°/s^2	363.80	3058.09
Twisting plane			
Maximum left twist	°	25.56	9.86
Maximum right twist	°	27.37	9.30
Maximum range of motion	°	43.17	14.96
Average velocity	°/s	12.98	3.27
Maximum velocity	°/s	161.20	85.76
Maximum acceleration	°/s^2	3921.08	5098.00
Maximum external moment	Nm	186.04	11.00

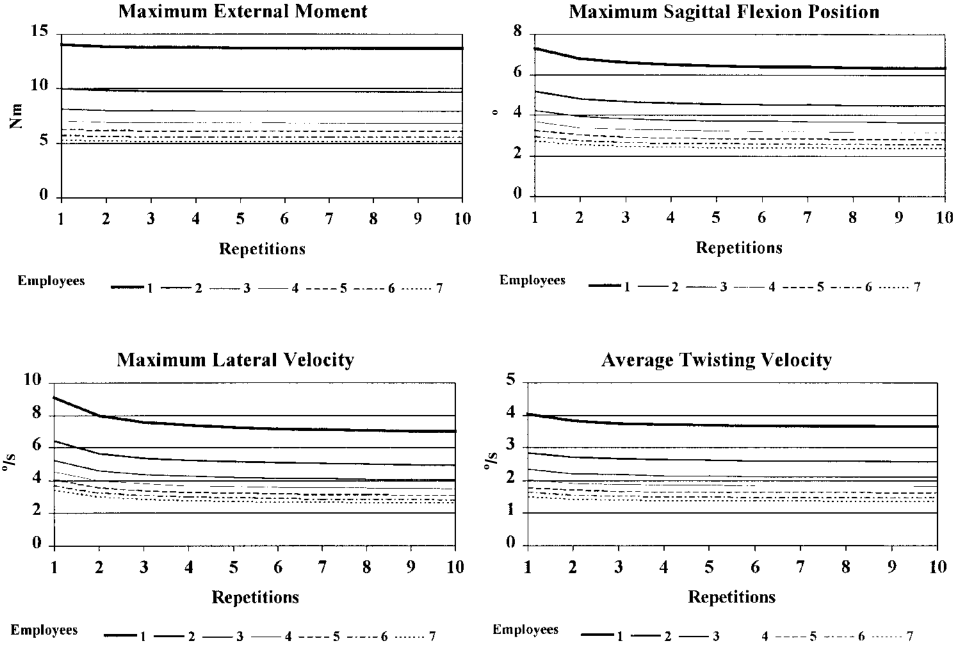

Figure 3. Standard error values around the mean for each of the variables identified.

velocity and average twisting velocity. These four variables are the task-dependent measures found by Marras *et al.* (1993, 1995) that, together, best distinguished between low- and high-risk of LBD jobs. The four graphs show the effect on each variable (in terms of reducing the SE about the mean) of increasing the number of employees *and* the number of repetitions of each task. These graphs show the effects on SE of all combinations of one to seven employees and one to ten repetitions of a task. Similar trends are seen in each graph. First, collecting data from additional employees initially lowered the SE of the estimate substantially, but the benefit diminished with the addition of three or more employees. Second, only small improvements were observed by adding greater numbers of repetitions for each task. The variance estimate was essentially unchanged with data from more than three repetitions of a task. Third, the curves for maximum external moment are more flat than the other variables. This is due to the large amount of variability *across* tasks that were seen with this variable, as compared with employee-to-employee or repetition differences. In other words, the amount of variability from one task to another was found to be much greater than that among or within employees for maximum external moment. Finally, it should be noted that the trends shown in figure 3 for these four variables were similar for all trunk motions observed and reported in table 3. The only differences in the curves across trunk kinematic variables was in their curvature. The relationships between the numbers of employees and repetitions monitored were very similar.

4. Discussion

These results have analysed the variability in trunk motions of employees performing a wide sample of MMH tasks. The analyses were performed on severely imbalanced data, in terms of numbers of employees monitored and repetitions collected per task. However, it was shown that, with this data set, reliable and accurate variance components analysis could be carried out for the trunk kinematic variables. These analyses were conducted on a subset of the data that included only tasks within which load weights and the heights at which they were handled across employees and repetitions did not vary. The data set used, however, was very large, including over 475 distinct MMH tasks, more than 500 employees performing these tasks, and nearly 3250 repetitions of task cycles. Therefore, this large number of tasks, employees, and repetitions ensured that the trends and findings reported here are representative of the general population of industrial jobs and employees.

The primary benefit of this investigation is that industrial-based information was used to determine the amount of data that are needed to adequately depict the trunk kinematics of MMH activities. To the authors' knowledge, this information does not currently exist in the literature. These analyses found that, even with the large amount of variability inherent in industrial MMH tasks, no additional improvement in accuracy of trunk kinematic measurement occurred after data from approximately three employees and three repetitions of a task were collected. These criteria were derived based on the similarity of trends of the SEs of the variables shown in figure 3 and the other trunk kinematic variables measured.

A secondary benefit from this analysis relates to the relative amount of variability between tasks, employees and repetitions. These results confirm earlier findings that the nature and design of MMH tasks are much more variable than either employee-to-employee or trial-to-trial differences within tasks. This suggests that trunk motions and subsequent risk of LBD are more a function of workplace factors than individual characteristics.

This idea can be further explored by comparing the variance estimators shown in table 3. Although trunk movements are measuring different activities (e.g. lateral versus sagittal versus twisting planes of motion, positions versus velocities verus accelerations), the ratios of these estimates are somewhat similar. That is, the ratios of the Variance (Employee (Task)) estimator to the Variance (Error) estimator range from 0.1 to 4.1 across all the trunk kinematic variables listed in table 3. However, this same ratio for maximum external moment is 16.9. This implies that moment (which is more a feature of workplace design issues) varies much more across tasks than within employees or repetitions of a task. This finding also was observed in the graphs shown in figure 3. That is, the reduction in SE due to additional repetitions of a task is much less for maximum external moment than for any of the trunk kinematic variables.

These findings have important ramifications for industrial ergonomists. In the data collection of trunk motions, these results provide guidance to investigators regarding the amount of information needed to depict trunk kinematic variables in an industrial setting as efficiently as possible. This can save the investigator valuable time when doing these types of field studies, and it also limits the involvement of employees who are being monitored and observed in the data collection process. It should be noted in figure 3 that none of the SEs for the variables is reduced to zero for the combinations of repetitions of employees plotted in these graphs. Theoretically, very small SEs can be derived using equation 1, but these employee and repetition numbers approach infinity and are impractical in industrial data collection.

It is important to emphasize that these findings, and the determination of appropriate data collection quantities, are limited to trunk kinematic variables. The variability of kinematic measures for other joints (e.g. wrist, elbow, knee) might have different distribution patterns. However, the methods used here to derive these numbers can be generally applied to other joints in the body.

5. Conclusions

This study has addressed the fundamental question of how much data are needed to characterize trunk kinematic and LBD risk parameters. By evaluating a large industrial database, the authors have been able to conclude that three trials and three employees performing a repetitive task should be adequate for describing trunk motions required of a task and for assessing LBD risk. This study reinforces the notion that LBD risk is more a function of job *design* than is individual *behaviour*.

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