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Influence of measurement accuracy on the application of the 1991 NIOSH equation

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Abstract

A relatively neglected topic in manual materials handling (MMH) research is the impact of the accuracy of task parameter measurements on the application of various assessment methods. A laboratory experiment was conducted to investigate the accuracy of NIOSH equation parameter measurements made by eight subjects following a 4-h training session. Five individual tasks were measured; two were single tasks and three were part of a multiple-component simulated palletizing operation. Significant differences between reference parameter measurements and average measurements made by subjects were found. The sensitivity analysis showed that frequency and horizontal location are the most important parameters. These parameters also tended to have the highest measurement errors. Recommendations for increasing the effectiveness of training programs for NIOSH equation users based on the results of the study are presented. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: NIOSH equation; Manual materials handling; Measurement accuracy

1. Introduction

The 1991 National Institute for Occupational Safety and Health (NIOSH) lifting equation (Waters et al., 1993) is an assessment method for lifting and lowering tasks. The equation is a revised version of the original equation published previously (NIOSH, 1981), and provides a recommended weight limit (RWL) based upon task parameters and the duration the task is performed. The RWL is defined as

$$\mathrm{RWL} = 23\,\mathrm{kg}\left[\frac{25}{H}\right][1 - 0.003|V - 75|] \times \left[0.82 + \frac{4.5}{D}\right]\mathrm{FM}[1 - 0.0032 \times A]\mathrm{CM},$$

where H is the horizontal location in cm, V is the vertical location in cm, D is the distance in cm, FM is the frequency multiplier, A is the asymmetry angle in degrees, and CM is the coupling multiplier. The actual load lifted or lowered divided by the RWL provides the lifting index (LI). LI values greater than 1.0 are assumed to represent tasks posing risk to the worker population.

One topic that has not been researched extensively is the accuracy of users' measurements of parameters required to apply the equation (as well as other MMH criteria). Sufficient accuracy and precision of measured parameter values are critical so that proper conclusions are drawn from the assessment. Poor accuracy and precision can lead to reduced sensitivity and specificity, which may ultimately lead to an inappropriate allocation of the resources appropriated for ergonomic improvements.

A convenient method of illustrating the effect of measurement error on the RWL (and subsequently, the LI) is to use the differential ($f'(x)\Delta x$, where Δx is the assumed error in this case). Since $f(x + \Delta x) \approx f(x) + f'(x)\Delta x$, the differential provides a reasonable estimate

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of the effect of a given error (assuming the error is not large).

For example, take the case of estimating the effect of measurement error in H on the RWL. Assume a lifting task has parameters such that the product of all multipliers except the horizontal multiplier is equal to 0.85. In this case, the RWL is equal to

$$\mathrm{RWL} = 23\,\mathrm{kg}\left(\frac{25}{H}\right)(0.85).$$

The differential with respect to H is equal to

$$-23\,\mathrm{kg}\left(\frac{25}{H^2}\right)(0.85)\,\Delta H.$$

The effect of a 1 cm. error in H (i.e. $\Delta H = 1$) can be estimated for different values of H. When $H = 25$, the differential is -0.78 indicating that the recommended weight limit would be reduced by 0.78 kg for a 1 cm. overestimate of H. When one considers how small a centimeter is in the scale of the workplace, the sensitivity of the multiplier to errors is quickly illustrated. When $H = 60$, the differential is -0.14. These two examples also illustrate the non-linear nature of the horizontal multiplier.

Recently, Dempsey and Fathallah (1999) examined the asymmetry multiplier of the 1991 equation. Using three independent sources of data, they concluded that there is substantial variation in how different individuals measure asymmetry when applying the equation in industry. Potential methods of increasing consistency of application include revising the multiplier and developing clearer instructional materials.

A study of the accuracy of 27 non-ergonomists' assessments of vertical location, horizontal location, asymmetry, coupling, and significant control was reported by Waters et al. (1998). The subjects measured parameters of an asymmetric lifting task in a laboratory eight weeks after a 7-h training session. Significant differences between measured and actual asymmetry values were found, and 41% of the participants rated coupling incorrectly. The authors concluded that a 1-day training class is sufficient to instruct users to properly measure the studied parameters. However, Burdorf and van der Beek (1999) recommend cautious interpretation since random sources of measurement error present in the workplace, as well as difficulties measuring frequency, may result in less favorable results for actual workplace use than those reported in a laboratory setting.

Although the revised NIOSH equation is widely used, there has been little epidemiological investigation of the equation. Waters et al. (1999) reported the results of a cross-sectional study of the relationship between the LI and prevalence of low-back pain in 50 jobs at four sites. A significant prevalence proportion ratio was found when comparing jobs with LI values greater than 2.0 but less than or equal to 3.0 compared to an unexposed group. The results did not indicate a dose-response relationship. Ultimately, the validity of the equation is related to the ability to control losses, particularly low-back disorders, associated with lifting and lowering. Clearly, additional epidemiologic study of the equation is needed (Dempsey et al., 1995; Leamon, 1994) to determine if the equation is valid.

Aside from the importance of measurement error to workplace assessments, these errors also have relevance to exposure assessments performed for epidemiologic research. In epidemiologic research, measurement error is one source of study bias that influences the validity of the results. When exposure variables are measured with some degree of error, and the error is constant irrespective of the value of the outcome classification, the point estimate of the effect of the association between exposure and outcome is reduced to some degree.

Exposure measurements may have multiple types and sources of error. The effects of these errors are usually complex and not easily predicted, and correction for these errors is often difficult (Flegal et al., 1991). Standardization of workplace measurements can help assure reliable estimates of exposure in epidemiological studies (Burdorf, 1992; Hagberg, 1992). Standardization can be enhanced by developing and testing methodologies for exposure assessment, which was one focus of the current study.

In summary, measurement error is relevant to exposure assessments, whether for the purpose of workplace assessment or for epidemiological research. The purpose of the current study was to assess users' measurement accuracy following a training course developed for field measurement of NIOSH equation parameters.

2. Methods

2.1. Subjects

Eight subjects (seven males and one female) participated in the study. All subjects held at least a BS degree in Engineering/Safety or other related fields and had limited experience in assessing MMH tasks in the field. All subjects work in the safety and health field, and had previous training on the application of psychophysical data, which require measurements similar to those required by the NIOSH equation.

2.2. Apparatus

All lifting tasks involved handling 5 kg. cardboard boxes (26 cm high, 40.6 cm wide and 37.7 cm deep) with 7.6 cm wide by 2.5 cm high cut-out handles. The subjects were provided with a spring scale to measure box weight, a tape measure to measure horizontal and vertical locations, and a protractor with reference guides to measure the asymmetry angles.

2.3. Procedures

Prior to data collection, the subjects underwent a 4-h training session. The 3.5 h lecture included definitions of parameters and methods of measuring the workplace and task parameters necessary to calculate the NIOSH lifting index. Approximately, 45 min of the lecture were devoted to issues specific to an ongoing epidemiologic study. The content of the training material and all variable definitions were based on the "Applications Manual for the Revised NIOSH Lifting Equation" (Waters et al., 1994). Actual RWL and LI calculations were not covered since the authors strongly recommend using computer software to perform the calculations. Throughout the training session, subjects asked pertinent questions about specific measurements. Measurement demonstrations were made by the authors during a 0.5 h interactive session for parameters measured with the protractor and tape measure (e.g., asymmetry, horizontal distance). After the training session, each subject consented to participate in the study and was asked to gather data on the simulated tasks.

A trained volunteer performed five simulated lifting/lowering tasks: (1) a symmetric lift, (2) an asymmetric lift, and (3) a palletizing operation consisting of three asymmetric lowering tasks. The tasks were chosen to represent asymmetric and symmetric tasks, and single- and multiple-task situations. Reference measurements were made by two of the authors with expertise in the NIOSH equation (both have analyzed several hundred lifting/lowering tasks in various workplaces using the equation). The projections of the midpoint of the ankles and knuckles of the volunteer onto the floor were marked with small circles. These were used to measure horizontal locations and asymmetry angles with a tape measure and protractor, respectively. These projections were removed before the experiment. For each angle, the asymmetry and sagittal lines were marked with pencil to obtain accurate angles (also removed before experiment). The placement of the volunteer's feet was marked with tape to decrease variability, and the positions for the origins and destinations of the different tasks were marked with tape for the same reason. The volunteer was made aware of the need for consistent foot and box placement. Prior to the experiment, the volunteer performed each task for several hours to assure consistency and repeatability of the task's reference measurements. The authors feel that the reference measurements are far more accurate than measurements made in the workplace, and that the variability in task performance is, for all practical purposes, negligible compared to the variability observed in the workplace. The reference values for parameters of all tasks are given in Table 1.

The first task (see Fig. 1a) was a single lift assumed to be continuously performed for a period of 45 min before performing a 1-h paper-work task, simulating a short-duration task. The task duration and rest break information were provided to subjects on paper in order to calculate the duration.

The second task (see Fig. 1b) was an asymmetric lifting task assumed to be continuously performed for a period of 2 h before taking a 30-min lunch break, simulating a long-duration task.

Tasks 3–5 (see Fig. 1c) simulated a palletizing operation. The volunteer lowered six boxes (three layers of two boxes) from a table at his right side and stacked them (three levels) at floor level (see Fig. 1c). It was assumed that each of the layers constituted a single task. For a given layer (task), the two boxes comprising that layer had different horizontal distances and asymmetries. For these variables, the average parameter values of the two boxes were used for the reference measurements. For each task, the frequency was 4 lowers per minute. The operation was assumed to be continuously performed during a 4-h period, simulating a long-duration task.

All the lifting/lowering tasks were performed with significant control and the box was rated as having "fair" coupling characteristics. The volunteer was instructed not to move his feet while performing the tasks. Also, the

Table 1
Reference parameter values for the five lifting/lowering tasks[a]

Task	V_O	V_D	H_O	H_D	A_O (deg)	A_D (deg)	F	Duration
1-Symmetric	25.4	99.1	48.3	83.8	0	0	6	Short
2-Asymmetric	22.9	99.1	45.7	68.6	0	48	4	Long
3-1st palletizing	149.9	25.4	66.0[b]	58.4[b]	50[b]	61[b]	4	Long
4-2nd palletizing	124.5	50.8	66.0[b]	58.4[b]	50[b]	61[b]	4	Long
5-3rd palletizing	99.1	76.2	66.0[b]	58.4[b]	50[b]	61[b]	4	Long

[a] V_O = vertical height at the origin; V_D = vertical height at the destination; H_O = horizontal distance at the origin; H_D = horizontal distance at the destination; A_O = asymmetry at the origin; A_D = asymmetry at the destination; F = frequency (lifts or lowers per minute). All distance measures are in centimeters.

[b] Average values, see text for explanation.

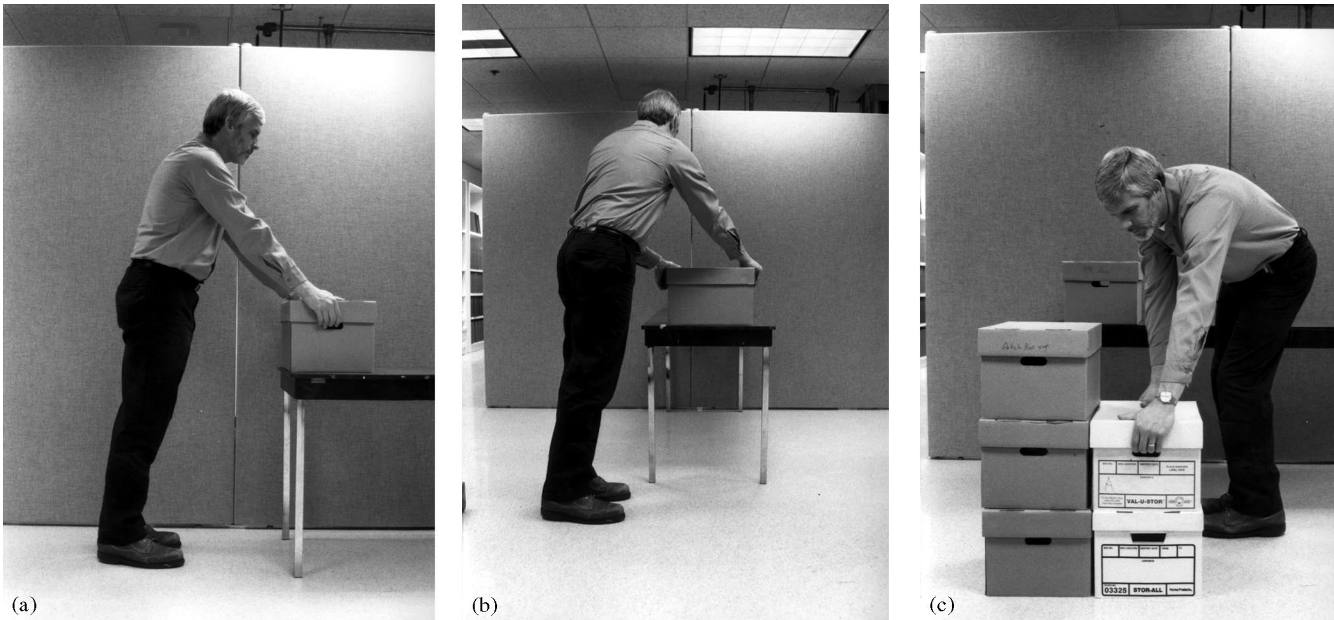

Fig. 1. Illustration of destination for symmetric task (a), asymmetric task (b) and palletizing operation (c).

volunteer did not pause while the subjects made the measurements. This was meant to simulate situations in industry where the workers do not stop or pause while measurements are made.

Each subject started the data collection by using a spring scale to weigh one of the boxes. The subject then started recording vertical location, horizontal location and asymmetry at the origin and destination, coupling, frequency, weight and significant control while the volunteer continuously performed the symmetric task, asymmetric task, and palletizing operation, consecutively. Locations, asymmetry angles, and frequency were measured with a tape measure, protractor, and watch, respectively. Subjects did not interact with the experimenters and were not constrained as to how the measurements were made. The volunteer stopped performing a given task and moved to the following one whenever the subject was through recording all the parameters. The subjects were provided with data sheets to record all information. Durations for all tasks were calculated after the measurements were completed using written information about the hypothetical tasks and the length of rest breaks presented earlier.

2.4. Data analysis

The mean and standard deviation of all subjects' measurements were calculated for weight (W), vertical distance at the origin (V_O) and destination (V_D), horizontal distance at the origin (H_O) and destination (H_D), asymmetry at the origin (A_O) and destination (A_D), frequency (F), and LI at the origin (LI_O) and destination (LI_D) for each of the tasks. The RWL and LI values for each task were calculated at the origin and the destination of the lift as described by Waters et al. (1994) with two exceptions. The value of H_D for Task 2 (68.6) and the values of H_O (66.0) for Tasks 3–5 exceed the maximum value of 63 cm. In these cases, the RWL is technically equal to 0 (and the LI $= \infty$) since the horizontal multiplier is 0 when the bounds are exceeded. However, the authors chose to ignore this violation for the calculations since infinity values exclude meaningful statistical analysis. The multiplier itself accepts values greater than 63; thus, the value of the multiplier with the actual values were used. This is not unlike situations in industry where practitioners use a similar method or use a value of 63.

To test for significant differences between the subjects' measurements and the reference value (accuracy), a two-tailed t-test statistic was computed for each variable.

2.5. Sensitivity analysis

The sensitivity of Task 4 LI (destination was used) to changes in parameter values was evaluated by calculating the effect on the LI of using the minimum and maximum values of the individual multipliers. Task 4 was chosen arbitrarily, and this analysis does not provide a general result, rather provides a method for illustrating the effects of measurement error. This type of example has been found to be an effective training tool to show that measurement error should be taken seriously. Similar analyses can be conveniently performed for any task with dedicated software or a spreadsheet.

The minimum and maximum multiplier values represent the extremes of errors of under- or over-measurement, respectively. The six parameters studied included vertical location, travel distance, asymmetry angle, horizontal location, frequency, and load weight. The sensitivity is expressed by the range in LIs and the ratio of the highest to the lowest LI. This analysis provides insight into the range of potential errors that can be caused by individual parameter measurement errors for a fairly typical task.

Second, an analysis was made of the effect of measurement error on the calculated LI. Measurement variability for each of the six parameters was expressed by the standard deviation, and, subsequently, the 95% confidence interval around the LI was calculated. The reference values were used for each parameter. Each standard deviation was then halved, and the procedure was repeated to illustrate the effect of reduced measurement error (variability). It was assumed that the standard deviation represents random measurement error in the parameters. The standard deviation values for the displacement measurements were all set to 5 cm. to enhance comparison across parameters, and values for the other parameters were set by examining the experimental results.

3. Results

The reference values, descriptive statistics of measurements made by the subjects (measured values), and results of *t*-tests for each parameter of all tasks are given in Table 2. Significant differences are for testing the hypothesis that the mean measured value is equal to the reference value. There was an overall tendency to underestimate the reference values.

For Task 1, there was a significant difference between reference values and mean measured values for the vertical and horizontal locations at the origin. In spite of these differences, the mean LI value from the measured values was not significantly different from the reference LI value. Overall, the subjects had a tendency to underestimate the measures. Duration was calculated correctly as short by all eight subjects, significant control was correctly rated yes by five subjects, and coupling was rated correctly as fair by six subjects (two incorrectly rated coupling as good). Although the coupling rating algorithm from Waters et al. (1994) was used for training, the subjects appeared to rate coupling more subjectively.

For Task 2, there was a significant difference between the reference value and the mean measured value only for vertical location at the destination. This task had similar variation in LI values to Task 1. Duration was calculated correctly as long by three subjects (five subjects rated duration as medium), significant control was correctly rated as yes by four subjects, and coupling was rated correctly as fair by seven subjects (one incorrectly rated coupling as good).

For Tasks 3–5, there was a significant difference between reference values and mean measured values for the

Table 2
Comparison between the reference and measured values for the five tasks[a]

Task		Measured Parameters of NIOSH Equation								Calculated Lifting Indices	
		Weight	Vertical Location$_O$	Vertical Location$_D$	Horizontal Location$_O$	Horizontal Location$_D$	Asymmetry$_O$	Asymmetry$_D$	Frequency	Lifting Index$_O$	Lifting Index$_D$
1	Reference	5.0	25.4	99.1	48.3	83.8	0	0	6.0	0.8	1.2
	Measured mean (SD):	4.9 (0.4)	21.0[b] (2.5)	85.2 (25.3)	40.3[b] (5.5)	80.3 (9.1)	0	0	6.5 (2.5)	0.6 (0.2)	1.0 (0.4)
2	Reference	5.0	22.9	99.1	45.7	68.6	0	48	4.0	1.3	1.9
	Measured mean (SD):	4.9 (0.4)	21.1 (2.5)	95.0[b] (2.6)	47.0 (7.8)	65.1 (17.6)	0	51.6 (7.2)	5.3 (2.8)	1.3 (0.2)	1.8 (0.5)
3	Reference	5.0	149.9	25.4	66.0	58.4	50.0	61.0	4.0	2.3	2.0
	Measured mean (SD):	4.9 (0.4)	125.4 (47.2)	20.6[b] (3.8)	48.4[b] (15.9)	53.5 (18.4)	39.4[b] (8.6)	37.0[b] (11.7)	5.3 (3.8)	1.4[b] (0.8)	1.5 (0.7)
4	Reference	5.0	124.5	50.8	66.0	58.4	50.0	61.0	4.0	2.0	1.8
	Measured mean (SD):	4.9 (0.4)	105.9 (33.9)	47.5 (8.6)	52.1 (21.8)	53.9 (19.1)	39.4[b] (8.6)	40.1[b] (7.6)	5.3 (3.8)	1.3[b] (0.7)	1.3 (0.7)
5	Reference	5.0	99.1	76.2	66.0	58.4	50.0	61.0	4.0	1.6	1.4
	Measured mean (SD):	4.9 (0.4)	90.0 (33.2)	65.4 (20.7)	50.6 (18.2)	53.2 (17.7)	39.4[b] (8.6)	40.1[b] (7.6)	5.3 (3.8)	0.9[b] (0.8)	1.0 (0.9)

[a] Subscript O refers to origin and subscript D refers to destination.
[b] Significant at $p < 0.05$.

Table 3
Sensitivity of the LI to the possible range of individual parameter values for Task 4 (destination)[a]

Parameter	Possible range of multipliers		Multiplier in lifting task	Possible range in LI (min–max)
	Minimum–maximum	Ratio max/min		
Horizontal location	0.40–1.00	2.50	0.43	0.78–1.95
Vertical location	0.70–1.00	1.43	0.93	1.68–2.41
Travel distance	0.85–1.00	1.18	0.88	1.59–1.87
Asymmetry	0.57–1.00	1.75	0.80	1.45–2.54
Frequency	0.13–1.00	7.69	0.45	0.81–6.27
Coupling	0.90–1.00	1.11	0.95	1.72–1.91

[a]Subscript O refers to origin and subscript D refers to destination.

Table 4
Effect of measurement error on the Lifting Index in the 1991 NIOSH lifting equation, given a lifting task with LI = 1.8

Parameter	Reference value	LI calculation with measurement error		LI calculation with reduced measurement error	
		SD	95% CI	SD	95% CI
Horizontal location (cm)	58.4	5.0	1.55–2.06	2.5	1.68–1.93
Vertical location (cm)	50.8	5.0	1.75–1.85	2.5	1.77–1.82
Vertical travel distance (cm)	73.7	5.0	1.78–1.81	2.5	1.79–1.81
Asymmetry angle (^{0})	61	7.3	1.72–1.89	3.7	1.76–1.84
Frequency (lifts/min)	4	1.5	1.24–3.67	0.7	1.47–2.31
Coupling	0.95	na	na	na	na
Weight (kg)	5	0.4	1.54–2.05	0.2	1.69–1.91

vertical and horizontal locations at the origin. Additionally, there was a significant difference between reference values and mean measured values for the vertical location at the destination and horizontal location at the origin. For Task 4, the mean LI value for the origin was significantly different from the reference LI value. Duration was calculated correctly as long by all eight subjects, significant control was correctly rated yes by four subjects for Task 3 and by five subjects for Tasks 4 and 5, and coupling was rated correctly as fair by seven subjects for all three tasks (one incorrectly rated coupling as good).

3.1. Sensitivity analysis results

Table 3 provides the theoretical sensitivity analysis of the LI for Task 4 to errors in parameter measurements. The ratio of the maximum LI to the minimum LI expresses the variability in potential LI values that can be realized across the range of valid parameter values. The range for each parameter assumes all other parameters are measured correctly.

Table 4 provides confidence intervals for the LI using the standard deviations given for each parameter. The confidence intervals can be interpreted as follows. If repeated measurements of horizontal location were taken (assuming all other parameters were measured correctly), there would be 95% confidence that the true LI value lies between 1.55 and 2.06 when the standard deviation of measurements is 5 cm. Tables 3 and 4 indicate that errors in the measurement of asymmetry, frequency and horizontal location can have the largest effect on the LI.

4. Discussion

The measurement error results should be interpreted with respect to the sample size of eight, since the range of LI values (for example, 0.2–1.3 for the destination of Task 1) indicates practical significance, even if the differences are not statistically significant. On the other hand, there was also one instance of systematic error. The standard deviation for V_D for Task 1 is 25.3 cm. In this case, a participant misunderstood a measurement strategy presented. Comparing the standard deviation for V_D and V_O for Task 1 shows the substantial influence of this one subject. This subject's errors also affected the vertical location measurements of the origin for Tasks 3–5 and the destination of Task 5. The instructor stressed the importance of making the origin and destination measurements at the points when the load first leaves the surface and when the load first touches down, respectively.

When the load is lifted from or placed on a surface such that measurement of vertical location becomes difficult due to obstructions, the instructor indicated that the vertical location can be taken relative to the top of the surface and the height of the surface can be added to this value. However, a subject did not add the height of the surface when using this technique, causing the large variation. The training program was revised to avoid such confusion in the future.

The authors believe that the range of errors of other parameters can also be decreased through revising the content of training. The training program was revised to provide more focus on *techniques* for measuring parameters. Explicit techniques were provided for cases where the worker cannot stop to allow the analyst to make measures, as well as cases where the worker can stop. The latter case is ideal, but the authors have encountered numerous situations where minimal work stoppage is feasible. It should be noted that the experiment utilized the case where the worker does not stop, which enhanced measurement difficulty.

Several examples were also integrated into the training class that require participants to rate coupling and duration as well. For coupling, participants were asked to rate the handling of available objects, such as the overhead projector used for the training class. For duration, several textual examples were provided that included hypothetical durations of various activities that had to be rated as work time or rest time. Participants were asked to rate duration from this information, and the instructor then went through the calculations in detail. Finally, a session involving measurement of at least 3 lifting and lowering tasks was added. This was accomplished by having the instructors repetitively perform simulated tasks, and having groups of 3–4 participants measure the task parameters. There was substantial interaction among the group members and participants, which clarified the operational measurement of the parameters. When participants wanted more practice, additional tasks were measured. This provided a feedback mechanism on actual measurement that was not provided in the original training class (although errors made by participants were discussed individually after the experiment).

The sensitivity analysis provides insight into the effect that measurement error can have on LI values. Unfortunately, the most sensitive parameters were the ones associated with some of the highest experimental errors. Reducing measurement error by 50% (Table 4) indicates that the most benefit can be achieved by reducing errors in frequency, horizontal location and weight. Reducing errors in measurement of weight can be achieved through the use of more accurate and precise instruments. Reducing errors in frequency and horizontal location can be achieved through better training and measurement strategies, as well as more careful measurement at the workplace. For example, horizontal location is best measured by marking the midpoint between the ankles and knuckles with a coin or other means, and then taking a measurement (as opposed to simply holding up a tape measure and "eyeing" the measurement). If the worker cannot wait, the analyst can place their feet and hands in as similar position as possible after the worker moves and then take the measurement. Given the many workplace situations possible, several alternative methods should be provided to users, and the most desirable should be indicated.

4.1. Implications of results

Comparison of the results of this study to those of Waters et al. (1998) provides interesting insight. The main differences between the two studies are Waters et al. (1998) used a training session almost twice as long (7 h) as in the current study, only one task was measured, and frequency and duration were not measured. The results of the sensitivity analysis suggest that frequency is very important. The primary deficiency of the training program used for the current study was the lack of sufficient participation in measurements by subjects. Although the program has been modified to correct this problem, the results stress the importance of this type of training content in programs aimed at teaching users to correctly apply the equation. Given the results of both studies, and taking into consideration that the training was provided by individuals with expertise and experience applying the NIOSH equation, it is recommended that all users not familiar with measurements for the equation receive formal training.

This study also provides insight into the design of training programs for users of the 1991 NIOSH equation. Following the experiment, the participants were asked to provide feedback concerning the training program and the experiment. The comments tended to focus on feeling confident after the lecture, but being somewhat intimidated once the measurements began. This feedback, as well as the experimental results, led to improvements in the training program. The hands-on portion of the class involving measurement of the individual parameters was partially subsumed into the lecture with the instructor demonstrating the measurements. The hands-on portion then became more like the experiment in that participants each demonstrated their ability to measure all parameters of simulated tasks. We believe that there would have been reduced measurement error if the training program used for this study included a "practice" session. From these experiences as well as experiences with more diverse (with respect to education and job type) groups of users attending ergonomics short courses, it is recommended that strong emphasis is placed on actual measurement rather than lecture. Ideally, the most effective method is to visit a workplace and provide additional guidance and feedback to users. Several of the authors have used this approach with positive feedback.

Regardless of the training program used, the results indicate that measurement of horizontal location and frequency should receive priority. Frequency has the potential for the largest errors, given the fact that the possible range for the multiplier exceeds that of the multipliers for the other parameters (excluding cases where multipliers are 0 due to parameters being out of acceptable range). In fact, the magnitude of errors in the LI due to errors measuring horizontal location and frequency can make measurement errors in the other variables irrelevant for some tasks, i.e. a large error in frequency or horizontal location could be of the magnitude that the analysis will not be meaningful, regardless of other errors. Coupling and asymmetry also deserve note as parameters that should receive attention.

4.2. Study limitations

Several limitations of the study should be considered when interpreting the results. The first limitation is that five tasks were studied, all with the same box weight. Since the equation is multiplicative, errors can have different relative effects for different weights. Also, these five tasks do not represent the full spectrum of industrial lifting and lowering tasks. Likewise, the sample of eight subjects does not represent the full spectrum of NIOSH equation users. Although all subjects had safety and health training, different results may have been obtained if the participants had either no or extensive training and experience. The latter two scenarios represent individuals that use the equation.

A critical issue that this study did not address is the broader issue of the impact of job analysis strategies on parameter measurement error. One of the most challenging aspects of using the NIOSH equation (and other task analytic MMH approaches) in industry is determining just what the individual tasks are, and then determining what the 'typical' parameter values are. In some cases, jobs are sufficiently complex such that defining distinct tasks is extremely difficult or impossible (e.g., warehousing, truck loading/unloading, complex palletizing operations where products frequently change). Similarly, workers rarely perform repetitions of a particular task in the same manner. One only needs to consider a layer of a pallet to be a distinct task to appreciate the variability in parameter values. In this case, parameters actually become variables (see Dempsey (1999) for a more detailed discussion). This issue could potentially be as or more important than parameter measurement error alone. Additionally, MMH guidelines such as the NIOSH equation may only be useful to experts with a real understanding of the limitations and underlying assumptions of the method being applied (Buckle et al., 1992). This would imply use by those with training in ergonomics is appropriate, preferably with training in the physiological, psychophysical and biomechanical response of the human body to manual handling.

5. Conclusions

Based upon the results presented, as well as the authors' experiences with additional training sessions, the following recommendations can be made:

(1) Users of the NIOSH equation without MMH expertise should receive formal training, emphasizing practice of actual measurements in simulated conditions or at worksites.
(2) The length of training and/or the complexity of the tasks measured can affect users' ability to measure parameters.
(3) Due to the sensitivity of the LI to errors in frequency and horizontal location measurements, these parameters should receive priority when providing training. Additionally, these parameters are rather difficult to measure compared to the vertical locations (and hence distance traveled).
(4) The results illustrate the importance of testing a training program, and the current study provides an example of a methodology that can be used to test programs developed in the future.

References

Buckle, P.W., Stubbs, D.A., Randle, I.P.M., Nicholson, A.S., 1992. Limitations in the application of materials handling guidelines. Ergonomics 35, 955–964.

Burdorf, A., 1992. Exposure assessment of risk factors for disorders of the back in occupational epidemiology. Scand. J. Work Environ. Health 18, 1–9.

Burdorf, A., van der Beek, A., 1999. Letter to the editor. Appl. Ergonomics 30, 369–370.

Dempsey, P.G., 1999. Utilizing criteria for exposure and compliance assessments of multiple-task manual materials handling jobs. Int. J. Ind. Ergonomics 24 (4), 405–416.

Dempsey, P.G., Ayoub, M.M., Westfall, P.H., 1995. The NIOSH lifting equations: a closer look. In: Bittner, A.C., Champney, P.C. (Eds.), Advances in Industrial Ergonomics and Safety, Vol. VII. Taylor & Francis, London, pp. 705–712.

Dempsey, P.G., Fathallah, F.A., 1999. Application issues and theoretical concerns regarding the 1991 NIOSH equation asymmetry multiplier. Int. J. Ind. Ergonomics 23, 181–191.

Flegal, K.M., Keyl, P.M., Nieto, F.J., 1991. Differential misclassification arising from non-differential errors in exposure measurement. Am. J. Epidemiol. 134, 1233–1244.

Hagberg, M., 1992. Exposure variables in ergonomic epidemiology. Am. J. Ind. Med. 21, 91–100.

Leamon, T.B., 1994. Research to reality: A critical review of the validity of various criteria for the prevention of occupationally induced low back pain. Ergonomics 37, 1959–1974.

NIOSH, 1981. Work practices guide for manual lifting. NIOSH Technical Report No. 81-122 (U.S. Dept. of Health and Human Services, National Institute for Occupational Safety and Health Cincinnati, OH).

Waters, T.R., Baron, S.L., Kemmlert, K., 1998. Accuracy of measurements for the revised NIOSH lifting equation. Appl. Ergonomics 29 (6), 433–438.

Waters, T.R., Baron, S., Piacitelli, L.A., Anderson, V.P., Skov, T., Haring-Sweeney, M., Wall, D.K., Fine, L.J., 1999. Evaluation of the revised NIOSH lifting equation: a cross-sectional epidemiologic study. Spine 24, 386–395.

Waters, T. R., Putz-Anderson, V., Garg, A., 1994. Applications Manual for the Revised NIOSH Lifting Equation. CDC/NIOSH US Department of Health and Human Services Public Health Service, Cincinnati, OH.

Waters, T.R., Putz-Anderson, V., Garg, A., Fine, L.J., 1993. Revised NIOSH equation for the design and evaluation of manual lifting tasks. Ergonomics 36 (7), 749–776.