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An Evaluation of the NIOSH Lifting Equation: A Psychophysical and Biomechanical Investigation

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Using the results of psychophysical and biomechanical experiments, NIOSH (National Institute for Occupational Safety and Health) Recommended Weight Limit (RWL), the Lifting Index (LI), the form of the asymmetry multiplier, and the criterion for compression force were investigated. Analysis of the results indicated a significant difference between the NIOSH RWL and the reported Maximum Acceptable Weight of Lift (MAWL). Contrary to the NIOSH lifting equation, the form of the asymmetry multiplier was found to be non-linear. The overall average of peak compression force on the L5/S1 was 3685 N. Fifty-eight percent of all compression forces reported in the biomechanical experiment were found to exceed the suggested 3400 N set by NIOSH guidelines. These results support previous research findings on the validity of NIOSH guidelines.

NIOSH lifting equation recommended weight limit asymmetry multiplier lifting index horizontal multiplier

1. INTRODUCTION

The NIOSH (National Institute for Occupational Safety and Health) lifting equation was designed to evaluate the risk of lifting tasks with respect to low back injury (Waters, Putz-Anderson, Garg, & Fine, 1993). The equation is widely accepted and used throughout industry in setting acceptable lift

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limits for workers. In an effort to refine and broaden the equation's application, it was revised in 1991. Included were changes made to the factorial constants of each original component along with the introduction of a coupling multiplier and asymmetrical determinant. Each of the six multipliers is used to reduce the load constant of 23 kg. The load constant is the maximum recommended weight for lifting under normal conditions. Although the NIOSH equation has been available since 1991, very little is known about the behavior or the practical implication of the Recommended Weight Limit (RWL) under real-life situations.

The objective of this study is to evaluate the internal validity of the NIOSH lifting equation with the results of psychophysical and biomechanical data obtained from laboratory studies involving manual lifting tasks performed under different combinations of task related conditions, namely, three twisting angles (30, 60, 90°) and two lifting frequencies (3 and 6 lifts/min). In particular, the following issues will be discussed:

1. Evaluation of the differences between the RWL and the Maximum Acceptable Weight of Lift (MAWL) obtained from this study;
2. Estimation of the Lifting Index (LI) of the different task conditions studied;
3. Investigation of the form of the asymmetric multiplier in the revised NIOSH equation and its applicability to the tasks discussed in this study;
4. Examination of the criterion set by NIOSH guidelines for the acceptable compression force.

2. LITERATURE REVIEW

Since the NIOSH published its original equation in 1981 for calculating recommended weights for manual lifting tasks, countless companies have used the equation to identify those tasks that have a risk of low back injuries (Auguston, 1995). Recent findings by many researchers (Auguston, 1995; Dempsey & Fathallah, 1999; Hidalgo et al., 1995, 1997; Honsa et al., 1998; Jager & Luttmann, 1999; Karwowski, 1992; Karwowski, Caldwell, & Gaddie, 1994; Karwowski & Gaddie, 1995; Karwowski & Pongpatanasuegsa, 1991; Nussbaum, Chaffin, & Page, 1995; Wang et al., 1998), however, suggested that both the original equation and the revised version (1991) may be limited in their predictive powers for some kinds of lifting tasks. Karwowski and Brokaw (1992) showed that the 1991 equation was much more restrictive with respect to defining the acceptable jobs in terms of RWL than the older version of the equation (1981). It was showed that more that two thirds of the analyzed tasks exceeded the RWL and would need redesign.

Karwowski and Gaddie (1995) used a computer simulation model to examine the behavior of the 1991 revised NIOSH lifting equation under a variety of realistic industrial lifting tasks. The results indicate that under most of the examined lifting conditions (99.5% of the simulated cases), one can reasonably expect that an implementation of the 1991 lifting equation at the level of the Lifting Index of 1.0, which is designed to protect 90% of the mixed industrial working population, would necessitate redesign of manual lifting tasks according to threshold RWL (TRWL) values. The TRWL values are equal to or lower than (a) 13.0 kg for up to 1 hr of lifting, (b) 12.5 kg for less than 2 hrs of exposure, (c) 10.5 kg for lifting over an 8-hr shift (Karwowski, Gaddie, Jang, & GeeLee, 1999).

The NIOSH equations are based on models that do not take into account motions of the trunk, namely angular position, velocity, and acceleration during lifting tasks. Yet epidemiological studies have shown that the dynamic motion in lifting tasks is associated with an increased risk of low back injury (Auguston, 1995). Also of significance was the finding that the NIOSH equation was limited in its ability to correctly determine the risk level of a given task. Karwowski (1992) examined the consequences of the multiplicative model for combining lifting factors in the 1991 revised NIOSH lifting equation. It was indicated that the multiplicity concept does not hold over a broad range of normal lifting tasks. It was suggested that the assumptions of a multiplicative effect on the load constant must be carefully examined. Wang et al. (1998) conducted a survey to evaluate the relation between low-back discomfort ratings and the use of revised NIOSH lifting guide to assess the risk of manual materials handling (MMH) tasks. Ninety-seven MMH workers were surveyed on site in 15 factories. The survey showed that 42 of the 97 jobs analyzed had a recommended weight limit of zero, which was attributed to either a horizontal distance or a lifting frequency that exceeded the bounds of the NIOSH lifting index. Apparently, the limits for the horizontal distance and the maximum allowable frequency are too stringent to accommodate many existing MMH jobs. For the horizontal multiplier (HM), if the horizontal distance (H) exceeded 63 cm, then HM = 0. In real-world situations, it is not rare to have H greater than 63 cm. Also, for the frequency multiplier (FM), when work duration is shorter than 2 hr and lifting frequency (F) is greater than 10 lifts/min, then FM becomes zero. The conclusion of the study indicated that many frequent lifting tasks such as those observed in the brick making and fertilizer companies tend to have FM = 0. Apparently, the limits for the horizontal distance factor and the frequency factor are rather strict, resulting in many out-of-bounds cases. Jager and Luttmann (1999) investigated the rational behind the introduction of the 3400 N compression force on the lumbosacral disc by NIOSH 1991 guidelines. They reported that, regarding this biomechanical criterion, several inconsistencies and discrepancies are revealed when comparing the NIOSH substantiation approaches and the respective data of the literature sources.

In a study to investigate the relationships between the calculated NIOSH 1991 lifting index values, the estimated compressive forces on the lumbosacral joint (L5/S1), and the back injury incidence rate, Karwowski et al. (1994) reported that only 4.17% of the 24 lifting tasks studied were acceptable under the 1983 guide if the criterion of LI = 1.0 is adopted. The compression force design limit of 3400 N was exceeded in 62.5% of all tasks whereas the upper (permissible) limit of 6400 N was exceeded in 16.67% of the tasks.

Brinham and Garg (1983) reported that jobs having a mean lumbosacral disc compression of nearly 8000 N would result in disc injuries, whereas jobs with averaged 5400 N disc compression lead only to muscular strains. It is concluded that the 3400 N criterion is substantiated neither epidemiologically nor biomechanically by the provided sources.

Honsa et al. (1998) examined the validity of the NIOSH 1991 hand-to-container coupling factor (good, fair, and poor/no handle), which allowed for a discount in RWL if box handles are not optimal. It was observed that the fair handle, not the good handle, condition produced the least amount of fatigue. It was thus concluded that the discount for fair or poor handles given by NIOSH 1991 must be interpreted by ergonomists.

Nussbaum et al. (1995) investigated the form of the asymmetric multiplier through analysis of several asymmetric lifting tasks. The results suggest that there is a non-linear increase in injury risk with respect to asymmetry. Only moderate increases in risk were predicted for asymmetry of 0–30°, and sharply increasing risk as asymmetry reaches 90°. This is contrary to the form of the asymmetric multiplier as suggested by NIOSH 1991 guidelines, which assumed a linear increase with an increased angle of asymmetry.

Dempsey and Fathallah (1999) compared the reduction in the recommended weight of lift to sagittal plane lifting due to the presence of asymmetry in the lifting tasks using six previous studies. Table 1 shows a comparison between the average reduction in the MAWL of the six studies and the reduction that results from using the NIOSH lifting equation.

TABLE 1. Reduction in the Maximum Acceptable Weight of Lift (MAWL) Due to Asymmetry

	Angle of Asymmetry (°)		
Source	30	60	90
Average of six studies	11.0%	19.8%	24.9%
NIOSH lifting equation	9.6%	19.2%	28.8%

It is clear from the Table 1 that, whereas the reduction in MAWL that results from applying the NIOSH lifting equation is linear (constant reduction of 9.6%), the average reduction in MAWL of the six studies is non-linear. The reduction in MAWL is 8.8 and 5.1% when the angle of asymmetry changes from 30 to 60° and from 60 to 90°, respectively. The results of the aforementioned comparison pointed to the need of re-addressing the form of the asymmetric multiplier as suggested by NIOSH guidelines.

3. METHOD

The results of previously conducted psychophysical and biomechanical experiments (Elfeituri & Taboun, 1999) were obtained and summarized in order to use them for evaluating NIOSH lifting guidelines. The tasks studied involved manual lifting activities performed under limited ceiling heights at three twisting angles of 30, 60, and 90°. Two lifting frequencies were utilized, namely 3 and 6 lifts/min. A tote box (38 × 38 × 25 cm) filled with sand bags was lifted from the floor to a table 76 cm high. Thirteen experienced volunteer participants were involved in the experiments. The different task parameters as well as the detailed results of the MAWL and peak compression forces were reported in Elfeituri and Taboun (1999). The different task parameters were input into the NIOSH lifting equation to obtain RWL. The lifting index (LI) was calculated for each task condition by dividing MAWL by RWL. The form of the asymmetric multiplier, as suggested by the NIOSH equation, was evaluated using the three twisting angles studied. The peak compression forces obtained from the biomechanical experiment for the different task conditions were compared to NIOSH limiting criteria.

4. RESULTS

4.1. RWL

The Recommended Weight Limit (RWL) of the NIOSH lifting equation is the product of the load constant and six multipliers, which can be expressed as follows:

$$\text{RWL} = \text{LC} \bullet \text{HM} \bullet \text{VM} \bullet \text{DM} \bullet \text{AM} \bullet \text{FM} \bullet \text{CM}, \tag{1}$$

where LC—load constant (23 kg), HM—horizontal multiplier, VM—vertical multiplier, DM—distance multiplier, AM—asymmetry multiplier, FM—frequency multiplier, CM—coupling multiplier.

To determine the RWL of the task conditions manipulated in the psychophysical and biomechanical experiments, the six multipliers must be calculated first. The measurements and data needed are shown in Table 2.

TABLE 2. Summary of the Values of NIOSH Equation

Multiplier	Form	Parameter	Value
Load Constant (LC)	23 kg	23 kg	23 kg
Horizontal (HM)	25/H	H = 45 cm	0.556
Vertical (VM)	1 – (0.003 |V – 75|)	V = 14 cm	0.817
Distance (DM)	0.82 + (4.5/D)	D = 76 cm	0.879
Asymmetry (AM)	1 – (0.0032 • A)	A = 30°	0.904
		= 60°	0.808
		= 90°	0.712
Frequency (FM)	From tables[a]	3 lifts/min	0.550
		6 lifts/min	0.270
Coupling (CM)	good, fair, bad	Good	1

Notes. a—see Waters, Putz-Anderson, Garg, and Fine (1993).

By examining the values of the multipliers, it is clear that a horizontal distance of 45 cm in front of the spine resulted in a reduction of the load constant by 44.4% (from 23 to 12.79 kg). A horizontal distance of 45 cm is not uncommon in real-world lifting tasks. Wang et al. (1998) reported that in many actual situations, it is not rare to have a horizontal distance greater than 63 cm. Therefore, the horizontal distance of 25 cm in the NIOSH equation seems unrealistic.

The reduction in the load constant, caused by a vertical distance of 14 cm above the floor, is 18.3% (from 23 to 18.8 kg), which is not so significant compared to the reduction caused by the horizontal multiplier. The effect of the distance multiplier is also moderate. The most restrictive multiplier in the NIOSH lifting equation is the frequency multiplier. A lifting frequency of 3 lifts/min reduced the load constant by 45% (from 23 to 12.7 kg) whereas a lifting frequency of 6 lifts/min reduced the load constant by 73% (from 23 to 6.2 kg). Wang et al. (1998) pointed to the fact that frequent lifting tasks such as those observed in brick making and fertilizer companies would have a combination of lifting duration and lifting frequency that tend to have a frequency multiplier of zero resulting in RWL = 0.

Calculations for RWL under the different task conditions manipulated in the psychophysical experiment can now be achieved simply by substituting the aforementioned values into the equation for RWL. The data in Table 3 show the average box weight (MAWL), the resulting RWL, and the lifting index (LI) values for the six test conditions for all 13 participants. Because all task characteristics were controlled in the psychophysical study, (i.e., horizontal distance, vertical travel distance, box size, etc.), the calculated values for RWL were the same for all the participants. A comparison of MAWL with past data showed that data from the psychophysical study were comparable to those reported by Mital and Ramakrishnan (1999) and Bobick (1997). Thus, complete reliance on NIOSH RWL could lead to a weight limit, which could be very expensive, and unnecessary or impractical to achieve. Also, the difference between MAWL and RWL in Table 3 demonstrates the need to develop capability data that take into account more realistic task characteristics, in particular, the horizontal distance and the lifting frequency.

TABLE 3. MAWL, NIOSH RWL, and the Resulting Lifting Index

Twisting Angle (°)	Lifting Frequency (lifts/min)	MAWL (kg)	RWL (kg)	Lifting Index
30	3	11.71	4.57	2.56
	6	9.97	2.24	4.45
60	3	11.33	4.08	2.78
	6	9.78	2.00	4.89
90	3	10.95	3.60	3.04
	6	9.42	1.77	5.33

Notes. MAWL—Maximum Acceptable Weight of Lift, RWL—Recommended Weight Limit.

4.2. The Lifting Index

The Lifting Index (LI), used in the revised NIOSH equation of 1991, is a relative estimate of the level of physical stress associated with an analyzed lifting task. It is defined as the ratio of the weight of the load lifted (MAWL) to RWL. A value for LI that is 1.0 or lower is considered to be a safe load for handling for 99% of all men and 75% of all women. If LI is greater than 3, less than 25% of all men and 1% of all women have adequate strength to perform the lifting task. The higher the LI value, the more potentially hazardous is that weight for lifting under those specific conditions.

The LI values range from 2.56 to 5.33 with an overall mean of 3.84. Most of the LI values are greater than 3, which assumes a potential risk for the workers performing such tasks. A lifting index of more than 3 has been reported in previous studies. Wright and Haslam (1999) reported lifting indices of as high as 4.6 in an investigation into manual handling risks and controls within a soft drinks distribution center. Wang et al. (1998) reported that among the 97 jobs analyzed, 42 jobs had RWL = 0 (resulting in LI = ∞). Further, the results of analyzing the remaining 55 jobs showed that 14 jobs resulted in LI > 3 (average = 5.55), 30 jobs had a lifting index between 1 and 3, and only 11 jobs had a LI < 1. It was concluded that high LI values for the jobs analyzed were the result of inappropriate frequency and horizontal distance multipliers. The aforementioned results suggest that the value of LI as a measure of physical stress is questionable when applied to frequent lifting tasks with task characteristics differing from those defined in the NIOSH lifting equation (i.e., tasks performed in non-standard postures).

It is very clear from the data in Table 3 that all the participants who took part in the psychophysical study selected weights that exceeded the corresponding RWL and this in turn resulted in lifting indices greater than 1.

To examine which task condition contributed the most to the high LI values, analysis of variance was conducted on the data from all 13 participants. The results of ANOVA are shown in Table 4. The levels of both factors, twisting angle and lifting frequency, were found to be significantly different ($p < .01$). The higher the lifting frequency, the higher the LI value. The average LI was 2.79 at a lifting frequency of 3 lifts/min, whereas it was 4.89 at a lifting frequency of 6 lifts/min. This is another indication that the RWL obtained from the NIOSH lifting equation differs dramatically with increased lifting frequency. The same can be said about the change in LI values with the increase in the twisting angle. The results of the Duncan multiple range test indicated that the three angles differ significantly from each other with higher LI values observed at a 90^o twisting angle. The aforementioned results were similar to the findings of Bobick (1997) who reported a lifting index of 2.52 to 2.91 when comparing symmetric and asymmetric lifting tasks at chest and eye heights respectively.

TABLE 4. ANOVA Results for the Lifting Index

Source	*df*	*SS*	*MS*	*F* ratio
A: Participants	12	28.73	2.39	28.2[a]
B: Twisting angle	2	5.92	2.96	34.9[a]
C: Lifting frequency	1	85.70	85.70	1009.8[a]
B • C	2	0.51	0.25	3.0
Error	60	5.09	0.08	
Total	77	125.95		

Notes. a—significant at 1%.

The analysis of LI indicated that high LI values are attributed to very small values of the frequency and horizontal multipliers. It seems that the boundaries of the maximum allowable lifting frequency and the horizontal distance factors are too stringent to accommodate many lifting task parameters.

4.3. The Asymmetry Multiplier

The asymmetry multiplier (AM) in the NIOSH equation is defined for the 0–135^o range of the upper body twisting angle. Although the revised NIOSH lifting equation (Waters et al., 1993) attempts to simultaneously accommodate biomechanical, epidemiological, physiological, and psychophysical criteria, the asymmetry multiplier was only derived from biomechanical and psychophysical criteria (Dempsey & Fathallah, 1999). The justification for the form of AM comes primarily from three studies demonstrating decreases (of the order of 28.8%) in maximum acceptable weight of lift with a 90^o twisting angle (Nussbaum et al., 1995). AM was created as a linear interpolation between 0^o (no decrement) and 90^0 (28.8% decrement), with further extrapolation to 135^o of asymmetry.

It is evident that the NIOSH asymmetry multiplier is linear. Figure 1 shows the NIOSH asymmetry multiplier as a function of an asymmetric angle defined for the range from 0 to 120°. Figure 2 shows the change in MAWL of the psychophysical experiment as a function of the twisting angle. It is clear from this figure that the decrease in MAWL, with increased twisting angle, is non-linear in the 30–90° range. The decrease in MAWL is less steep for the 30 to 60° range than for the 60 to 90° range. Similar observations can be drawn from Figure 3. The increase in compression forces is steeper for the 60 to 90° range than the 30 to 60° range.

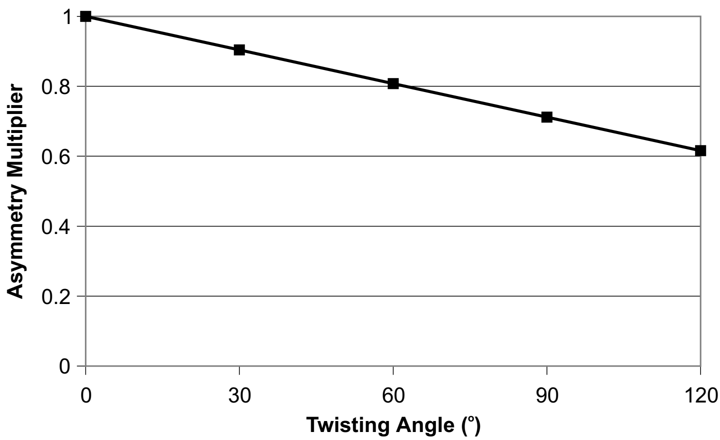

Figure 1. NIOSH asymmetric multiplier.

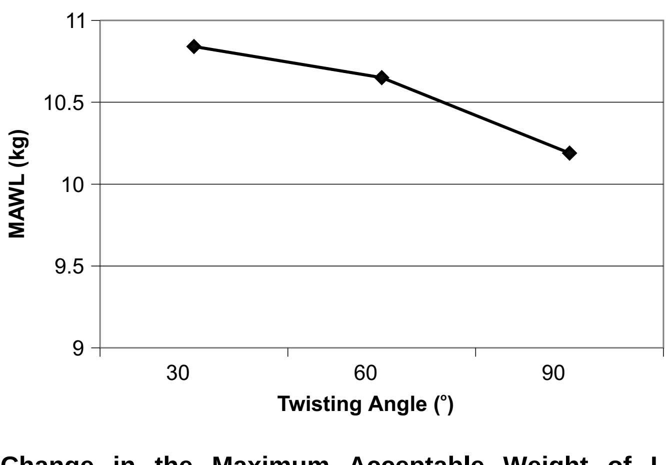

Figure 2. Change in the Maximum Acceptable Weight of Lift (MAWL) as a function of the twisting angle.

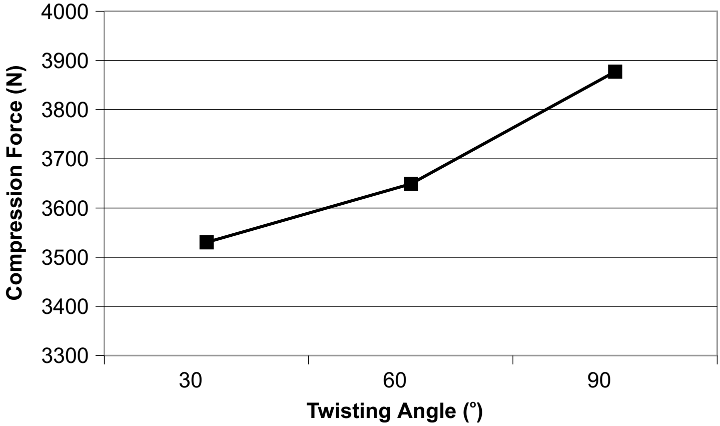

Figure 3. Change in compression force as a function of the twisting angle.

In general, the results of the psychophysical and biomechanical experiments are in conflict with the linear form of the asymmetry multiplier as presented by NIOSH. However, these results supported the findings reported by Nussbaum et al. (1995), who indicated a non-linear change in the musculoskeletal risk, derived from the change in muscular lengthened state, with change in the asymmetry angle from 0 to 90°. The risk rose only moderately from 0 to 60°, yet it rose with increasing slope as the asymmetry angle approached 90°.

The linear relationship given by NIOSH for the asymmetric multiplier may place undue emphasis on reducing asymmetry to 0°. The psychophysical and biomechanical experiments indicated that twisting angles smaller than 60° (moderate twisting) may be tolerated, if necessary, because they resulted in lower psychophysical and biomechanical costs as compared to twisting angles greater than 60°. Given the sharp increase in musculoskeletal risks reported in the literature (e.g., Chaffin & Page, 1993) for loads with 60 to 90° asymmetry, the justification for a linear asymmetry multiplier is suspect. It may be more reasonable to have substantially larger costs for tasks that require postural asymmetry greater than 90°.

4.4. Biomechanical Responses

The biomechanical load on the low back during lifting is determined by the weight of the load and the lifting posture. Three factors of the NIOSH equation are closely connected to biomechanical loading, namely, the load constant, the horizontal, and the vertical locations of the load. The NIOSH biomechanical criterion is based only on compressive forces on the lumbar vertebrae, which should not exceed 3400 N, neglecting anteroposterior and lateral shear forces. Another drawback of NIOSH biomechanical criterion is that it is based on static analysis of lifting tasks rather than the more realistic dynamic nature of lifting (Leskinen & Haijanen, 1996).

Many studies have revealed results to disc compression values between 2.5 and 8.0 kN without special emphasis to the 3.4 kN limit (e.g., Brinham & Garg, 1983). The overall average of peak compression forces on the L5/S1 disc in the biomechanical study was 3685.4 N with a range of 2037.5 to 6860.1 N. Out of the 78 total test conditions, 45 values (57.7%) were found to exceed the suggested 3400 N limit set by NIOSH guidelines. Even though the peak compression forces of this study were considered high, due to postural restrictions, they did not impose a high risk on the lumbosacral vertebrae of the participants of this study based on the findings of Brinham and Garg (1983) and Jager and Luttmann (1999) cited earlier. This seems logical as the participants were asked to lift loads they have accepted to lift in the psychophysical experiment. The psychophysical approach assumes that the participants can perceive the biomechanical and physiological stresses on their bodies and hence choose loads acceptable to their capabilities.

5. DISCUSSION

The revised NIOSH lifting equation has been shown to have limited applications in many realistic manual lifting situations. While considering twisting, it falls short of modeling lifting tasks performed under limited ceiling heights. Further, it provides a recommendation that is substantially lower than the average weight accepted by all 13 participants who participated in this study. The lack of agreement appears to be more for higher lifting frequencies. The difference between the MAWL of the present study, as well as other previous studies, and the RWL demonstrated the need for developing population capability data that take into account more realistic task characteristics. In particular, the frequency multiplier, the horizontal multiplier, and the load constant have to be addressed. Genaidy et al. (1998) reported that under ideal conditions, a load constant of 23 kg represents a “somewhat heavy” load based on the analysis of load distribution in a study aimed at estimating the amounts of load that correspond to various levels of load heaviness.

The horizontal multiplier was the topic of many criticizing articles in the literature. The 25-cm horizontal distance in front of the spine (distance of the hands from the midpoint of the ankles) is considered unrealistic in many real-world lifting tasks. The box width chosen for the psychophysical study (38 cm) is considered to represent the average box width used in manual lifting tasks in industry. Snook and Ciriello (1991) used boxes of three widths, namely 34, 49, and 75 cm for the well-known revised tables for estimating maximum acceptable weights and forces originally published in 1978. Table 5 represents the calculations for the horizontal distance using the box width used in this study and the three box sizes used in the Snook and Ciriello study. The horizontal distance is calculated by adding the 22 cm (distance from ankle to toes) to half the box width.

TABLE 5. Calculations for the Horizontal Multiplier

Study	Box Width (cm)	Horizontal Multiplier
Present	38	0.61
Snook and Ciriello (1991)	34	0.64
	49	0.54
	75	0.42

Because the RWL is inversely related to the horizontal distance, a small change in horizontal distance has a significant effect on the RWL. It is clear from the calculations in Table 4 that the horizontal multiplier is too restrictive. Figure 4 shows a sharp decrease in the horizontal multiplier as

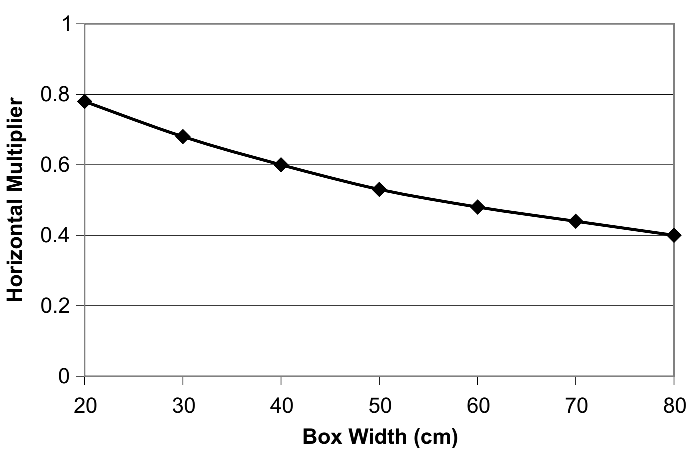

Figure 4. Horizontal multiplier as a function of box width.

a function of box size. The box sizes used in the aforementioned calculations are very common in industrial lifting tasks. Therefore, the horizontal distance of the revised NIOSH lifting equation need to be re-assessed to accommodate more realistic box sizes.

The lifting frequency is the most restrictive factor in determining NIOSH recommended weight limit. Based on NIOSH guidelines, a change in lifting frequency from 3 to 6 lifts/min resulted in a reduction of 51% in the RWL (from 0.55 to 0.27). The results of Elfeituri and Taboun (1999) indicated that the same change in lifting frequency (i.e., from 3 to 6 lifts/min) resulted in a 14.2% decrease in the MAWL and a 9.9% increase in heart rate. NIOSH frequency multiplier resulted in two to three times the effects indicated by the results of aforementioned study. Other previous research studies have reported similar findings. Hidalgo et al. (1995) cross-validated NIOSH lifting guidelines against data published in three previous studies (Ayoub et al., 1978; Mital, 1984; Snook & Ciriello, 1991). The results of the comparison indicated a significant difference between NIOSH limits and psychophysical limits for both low lifting frequency (1 to 4.3 lifts/min) and high lifting frequency (≥6 lifts/min). It was concluded that the RWL is substantially different from population limits in both Ayoub et al. and Mital studies.

The findings of this study, as well as the aforementioned studies, further demonstrated the limitation of the revised NIOSH lifting equation, particularly when it comes to designing and analyzing realistic industrial jobs.

REFERENCES

Auguston, A. (1995). Does the NIOSH lifting equation add up? *Modern Materials Handling, 12*, 51–53.

Ayoub, M., Bethea, N., Dievanayagm, S., Asfour, S., Bakken, G., Liles, D., et al. (1978). *Final report: Determination and modeling of lifting capacity*. Unpublished manuscript, Texas Tech University, Institute of Ergonomic Research, Lubbock, TX, USA.

Bobick, T. (1997). *The effects of lifting height and asymmetry on maximum acceptable weight of lift, average heart rate, and estimated biomechanical loading to the lumbar spine*. Unpublished doctoral dissertation, West Virginia University, USA.

Brinham, C., & Garg, A. (1983). The role of biomechanical job evaluation in the reduction of overexertion injuries. In *23rd Annual American Industrial Hygienists Association Conference* (pp. 138–144). Fairfax, VA, USA: American Industrial Hygiene Association Press.

Chaffin, J., & Page, G. (1993). Postural effects on biomechanical and psychophysical weight lifting limits. *Ergonomics, 37*, 663–676.

Dempsey, P., & Fathallah, F. (1999). Application issues and theoretical concerns regarding the 1991 NIOSH equation asymmetry multiplier. *International Journal of Industrial Ergonomics, 23,* 181–191.

Elfeituri, F., & Taboun, S. (1999). The effects of working in restricted workspaces on lifting capacity. In G. Lee (Ed.), *Advances in occupational ergonomics and safety* (pp. 95–100). Amsterdam, The Netherlads: IOS Press.

Genaidy, A., Karwowski, W., Christensen, D., Vogiatzis, C., Deraisheh, N., & Prins, A. (1998). What is 'heavy'? *Ergonomics, 41,* 420–432.

Hidalgo, J., Genaidy, A., Karwowski, W., Christensen, D., Huston, R., & Stambough, J. (1995). A cross-validation of the NIOSH limits for manual lifting. *Ergonomics, 38,* 2455–2464.

Hidalgo, J., Genaidy, A., Karwowski, W., Christensen, D., Huston, R., & Stambough, J. (1997). A comprehensive lifting model: Beyond the NIOSH lifting equation. *Ergonomics, 40,* 916–927.

Honsa, K., Vennettilli, M., Mott, N., Silvera, D., Niechwiej, E., Wagar, S., et al. (1998). The efficacy of the NIOSH (1991) hand-to-container coupling factor. In *Proceedings of the 30th Annual Conference of the Human Factors Association of Canada* (pp. 253–158). Calgary, Alta., Canada: Human Factors Association of Canada.

Jager, M., & Luttmann, A. (1999). Critical survey on the biomechanical criterion in the NIOSH method for the design and evaluation of manual lifting tasks. *International Journal of Industrial Ergonomics, 23,* 331–337.

Karwowski, W. (1992). Comments on the assumption of multiplicity of risk factors in the draft revisions of NIOSH lifting guide. In S. Kumar, (Ed.) *Advances in industrial ergonomics and safety IV* (pp. 905–910). London, UK: Taylor & Francis.

Karwowski, W., & Brokaw, N. (1992). Implications of the proposed revisions in a draft of the revised NIOSH lifting guide (1991) for job redesign: A field study. In *Proceedings of the 36th Annual Meeting of the Human Factors Society* (pp. 659–663). Santa Monica, CA, USA: Human Factors Society.

Karwowski, W., Caldwell, M., & Gaddie, P. (1994). Relationships between the NIOSH (1991) lifting index, compressive and shear forces on the lumbosacral joint, and low back injury incidence data based on industrial field study. In *Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting,* (pp. 645–657). Santa Monica, CA, USA: Human Factors Society.

Karwowski, W., & Gaddie, P.R. (1995). Simulation of the 1991 revised NIOSH manual lifting equation. In *Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting* (pp. 699–701). Santa Monica, CA, USA: Human Factors and Ergonomics Society.

Karwowski, W., Gaddie, P., Jang, R., & GeeLee, W. (1999). A population-based load threshold limit (LTL) for manual lifting tasks performed by males and females. In W. Karwowski & W.S. Marras (Eds.), *The occupational ergonomics handbook* (pp. 1063–1074). Boca Raton, FL, USA: CRC Press.

Karwowski, W., & Pongpatanasuegsa, N. (1991). Linguistic interpretation in human categorization of load heaviness. In *Proceedings of the 11th Congress of the International Ergonomics Association* (pp. 425–427). London, UK: Taylor & Francis.

Leskinen, T., & Haijanen, J. (1996). Torque on the low back and the weight limits recommended by NIOSH in simulated lifts. In *Proceedings of the 4th International*

Symposium on 3-D Analysis of Human Movement (session 4, paper No. 7). Grenoble, France: Université Joseph Fourier.

Mital, A. (1984). Maximum weight of lift acceptable to male and female industrial workers for extended work shifts. *Ergonomics, 27*, 1115–1126.

Mital, A., & Ramakrishnan, A. (1999). A comparison of literature-based design recommendations and experimental capability data for a complex manual materials handling activity. *International Journal of Industrial Ergonomics, 24*, 73–80.

Nussbaum, M., Chaffin, D., & Page, G. (1995). A biomechanical investigation of the asymmetric multiplier in the revised NIOSH lifting equation. In *Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting* (pp. 709–713). Santa Monica, CA, USA: Human Factors and Ergonomics Society.

Snook, S., & Ciriello, V. (1991). The design of manual handling tasks: Revised tables of maximum acceptable weights and forces. *Ergonomics, 34*, 1197–1213.

Wang, M., Garg, A., Chang, Y., Shin, Y., Yeh, W., & Lee, C. (1998). The relationship between low back discomfort ratings and the NIOSH lifting index. *Human Factors, 40*, 509–515.

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

Wright, E., & Haslam, R. (1999). Manual handling risks and controls in a soft drinks distribution center. *International Journal of Industrial Ergonomics, 24*, 311–318.