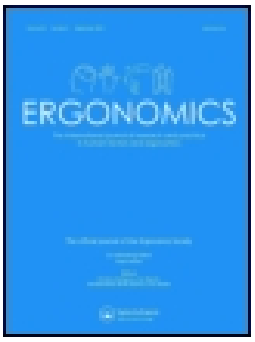

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A comprehensive lifting model: beyond the NIOSH lifting equation

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Keywords: Lifting; NIOSH lifting guidelines; Personal lifting safety index; Relative lifting safety index.

A comprehensive lifting model (CLM) for the evaluation and design of manual tasks was developed in two stages using 11 task, personal and environmental variables. In the first stage, the model was built using the psychophysical data. In the second stage, discounting factors of various variables were tested and adjusted using the physiological and biomechanical data. Two lifting indices are proposed to evaluate lifting tasks for a group of workers (relative lifting safety index or RLSI) and for an individual worker (personal lifting safety index or PLSI).

1. Introduction

The objective of this study was to develop a comprehensive lifting model (CLM) that can be used to determine limits for manual lifting and to evaluate tasks performed by individuals and groups of workers. The following considerations were taken into account during the proposed model development with reference to the revised NIOSH lifting equation (Waters *et al.* 1993):

(1) Weight lifting recommendations should not be limited to 75% of the female population and 99% of the male population. From an application standpoint, it is desirable to develop guidelines that accommodate various percentages of the working population.
(2) Weight lifting recommendations should include gender as an input variable since there are significant differences between males and females in terms of lifting capacity.
(3) Lifting capacity should be provided for different task durations instead of integrating the guidelines into one category (i.e. 2–8 h). Physiological studies demonstrated that the amount of load lifted significantly affects endurance time, which is defined as the limit of continuous work until the lifting task cannot be maintained any longer due to physical exhaustion (Genaidy and Asfour 1989, Genaidy *et al.* 1990, Asfour *et al.* 1991a,b).
(4) The upper limit for lifting frequency should be increased since physiological studies suggest that continuous lifting could be performed up to 16 times/min.

(5) The NIOSH weight lifting guidelines were developed for moderate ambient temperature (e.g. 19 – 26°C) and 35 to 65% relative humidity. These guidelines could be extended to incorporate the heat stress effects (Hafez 1984).
(6) New physiological and biomechanical tolerance limits generated in the ergonomics literature should be incorporated in developing weight lifting guidelines instead of basing those criteria on a matter of judgement.
(7) The asymmetric multiplier should only be based on dynamic lifting tasks and should not include data gathered from studies on static lifting tasks.
(8) The lifting model should be totally data-driven and should not include any human judgement. This will require reassessment of different multipliers used in the 1991 NIOSH lifting equation.

Based on the aforementioned considerations, the formulation of a lifting model proposed here agrees with the conceptual approach upon which the revised NIOSH lifting equation is based (i.e. multiplicative model with weight constant and discounting multipliers), but disagrees with a number of decisons made by the committee of experts who helped to develop the equation. Some of these differences are based on scientific theory and others are rooted in philosophical differences.

The revised NIOSH equation was designed to avoid gender-, age- or fitness-based recommended weight limits due to consideration of the Equal Employment Opportunity legislature and the Americans with Disabilities Act. However, there are many instances when the occupational medicine physician is required to make practical decisions for returning the rehabilitated employees to work. Frequently, these decisions are based on hunches. The comprehensive lifting model should help to fill this gap in order to assist physicians in these circumstances. In other situations, some delivery companies in service industries tend to staff their operations with young male workers. It would be unwise to equate these worker groups with the general employee population.

2. Model development

The comprehensive lifting model was developed in two stages. In the first stage, the model made use of psychophysical data relevant to evaluation and design of manual lifting tasks. In the second stage, discounting factors of various parameters in the model were tested and adjusted using the physiological and biomechanical data. The rationale for building the model in two stages was based upon the hypothesis proposed and tested by Karwowski (1983) and Karwowski and Ayoub (1984). This hypothesis stated that combining the acceptability of the physiological and biomechanical stresses should lead to an overall measure of lifting task acceptability, namely, the acceptability of the psychophysical stress.

The comprehensive lifting model was formulated as follows:

$$LC = W_B \times H \times V \times D \times F \times TD \times T \times C \times HS \times AG \times BW$$

where:

LC = lifting capacity (kg);
W_B = base weight, i.e. the maximum load acceptable to different percentages of worker population (kg);
H = factor for horizontal distance (cm) away from the body with respect to the mid-point between the ankles;

V = factor for vertical distance from the floor to the hands at the origin of lift (cm);
D = factor for vertical travel distance of the hands between origin and destination of lift (cm);
F = lifting frequency factor (times/min);
TD = task duration factor (h);
T = twisting angle factor (°);
C = coupling factor;
HS = heat stress factor (°C wet bulb globe temperature (WBGT))
AG = age factor (years); and
BW = body weight factor (kg).

The above multipliers are defined and illustrated in figures 1 to 10, respectively.

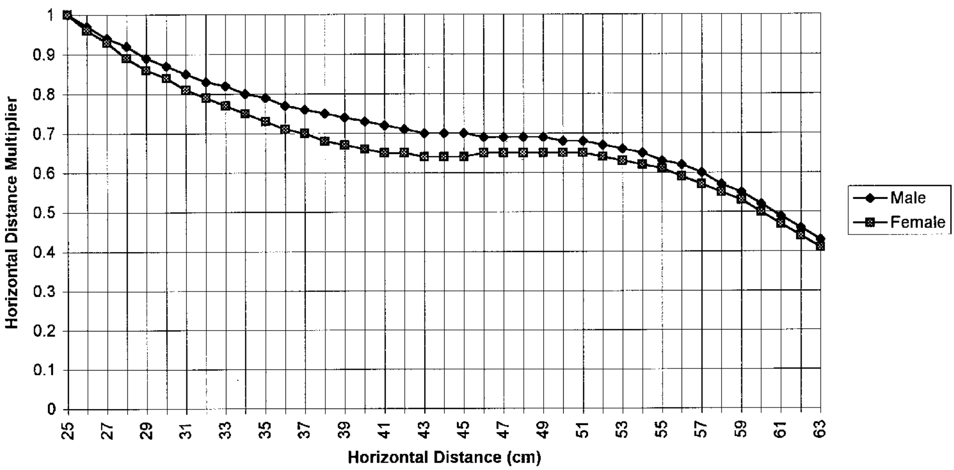

Figure 1. Horizontal distance multiplier.

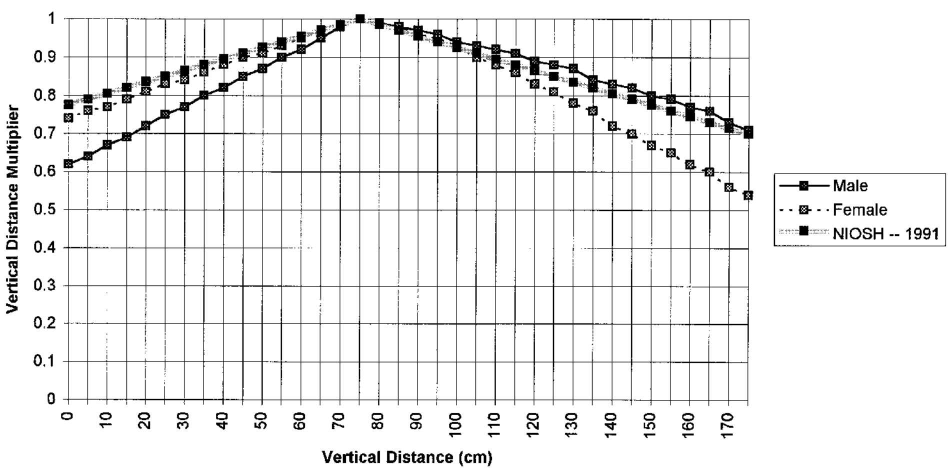

Figure 2. Adjusted vertical distance multiplier.

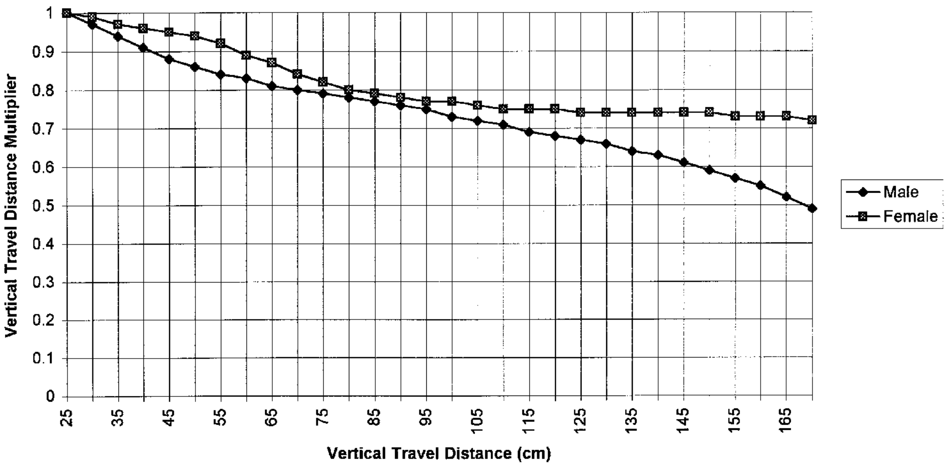

Figure 3. Vertical travel distance multiplier.

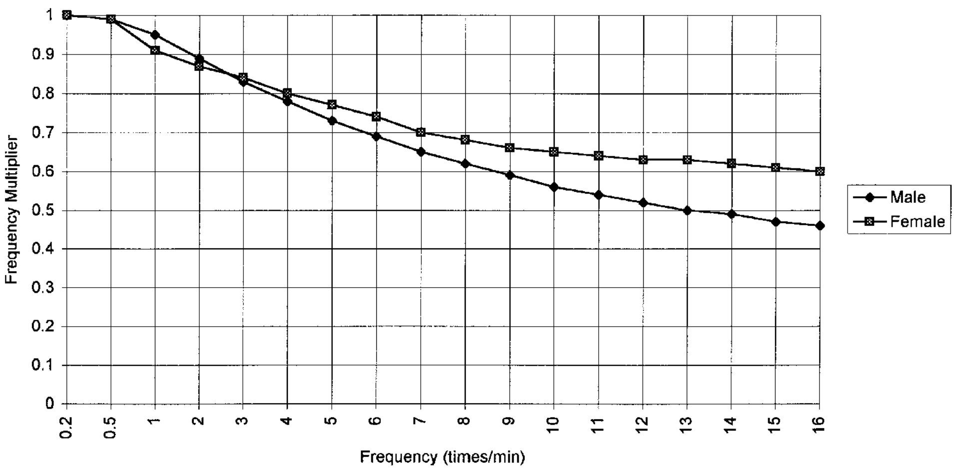

Figure 4. Frequency multiplier.

2.1. *First-stage model development and testing*

2.1.1. *Development:* In the first-stage of model development, the base weight data for manual lifting were established based on the maximum acceptable weight data reported by Snook and Ciriello (1991) for the following conditons: a 1 time/day frequency; a 25-cm vertical travel distance, a 26-cm vertical distance; and a 37-cm horizontal distance. A normal distribution was assumed so as to compute the maximum acceptable values of weight lifted for various percentages of worker population. The validity of this assumption is a function of the sample size of data collected, and may particularly impact the low and high ends of the normal distribution.

The 75% female population limit was equal to 23·3 kg and is equivalent to the maximum load provided by the 1991 NIOSH equation (Waters *et al.* 1993). On the

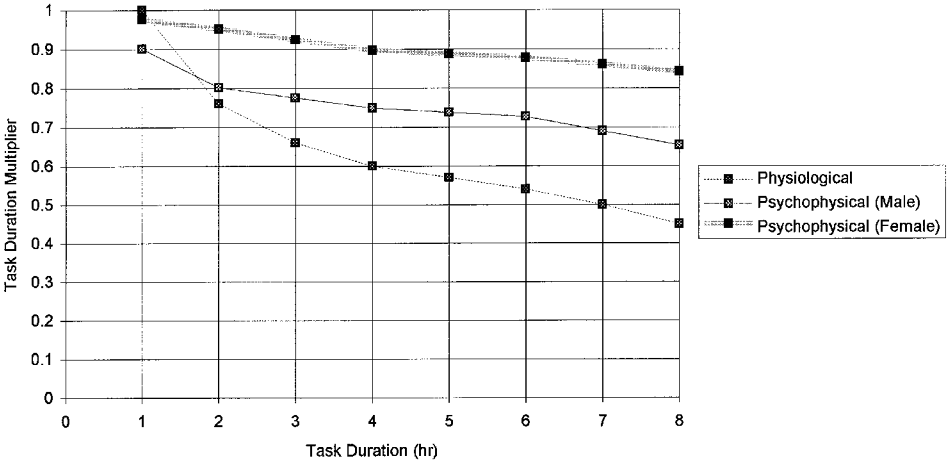

Figure 5. Comparison of task duration multipliers for physiological and psychophysical criteria.

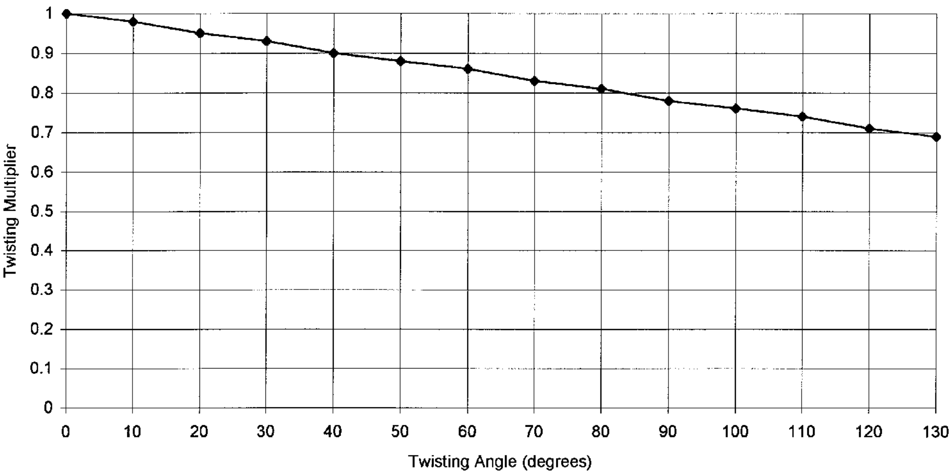

Figure 6. Twisting multiplier.

other hand, the 95% male population limit is less than 20 kg, a value lower than the 23·0 kg recommended by NIOSH (Waters *et al.* 1993) for the 99% male population limit. The 23·0 kg limit corresponds to the 93% male population limit in the present study, which is in agreement with psychophysical cross-validation of the NIOSH lifting equation (Hidalgo *et al.* 1995).

The horizontal distance, vertical distance at origin of lift, vertical travel distance, and frequency multiplier curves were formulated on the basis of data generated by Snook and Ciriello (1991), Ayoub *et al.* (1978), and Ciriello *et al.* (1993). As pointed out earlier, for the twisting angle, the data obtained for dynamic lifting tasks were chosen since these are more representative of the tasks

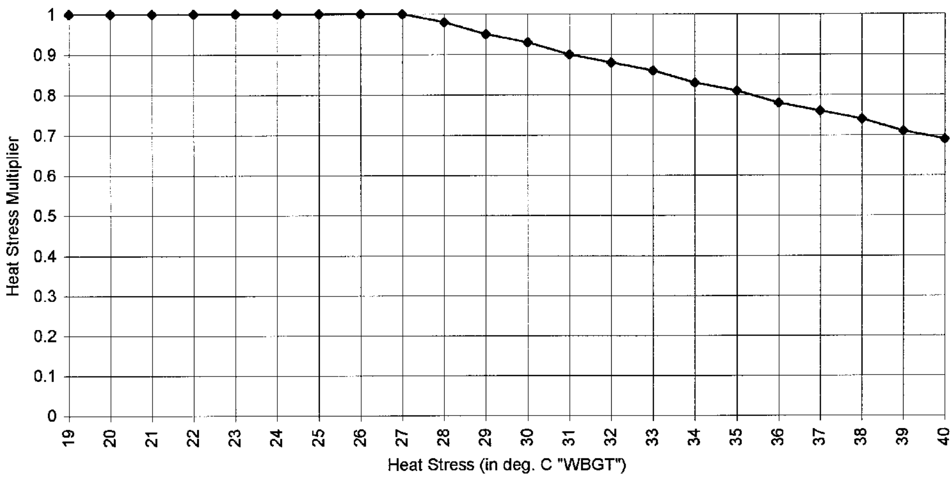

Figure 7. Heat stress multiplier.

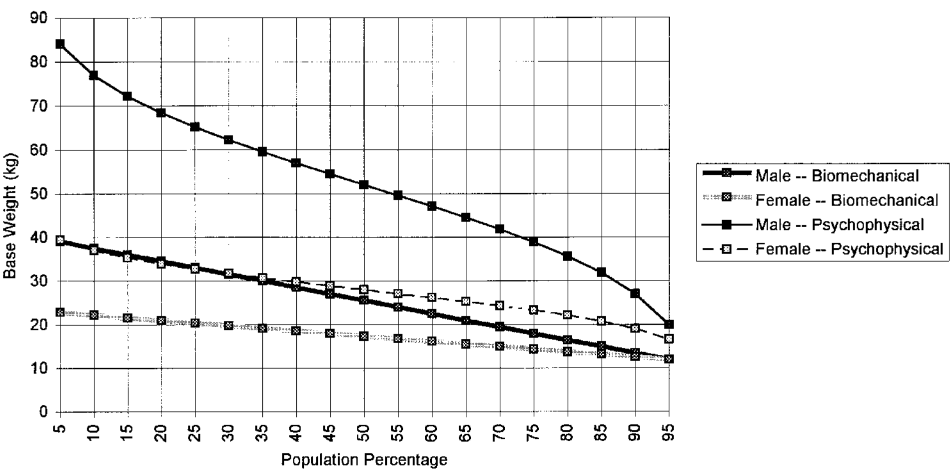

Figure 8. Base weight multipliers.

encountered in industry (Asfour *et al.* 1984, Garg and Badger 1986, Mital and Fard 1986).

The subject literature review suggested that task duration had no effect on the maximum acceptable weight of load at lower frequencies ($\leqslant$4 times/min), and a significant effect at higher frequencies of lift (>4 times/min). Thus, the multipliers suggested in this study are based on the industrial population of Mital (1983) and their application was restricted to frequencies higher than 4 times/min.

The coupling factor was categorized into three levels (Mital *et al.* 1993), i.e.: (1) good and comfortable handles/firm holds to initiate the lift (multiplier = 1), (2) poor quality handles/limited or slippery hold (multiplier = 0·925), and (3) no handles/holds to initiate lift (multiplier = 0·85). The heat stress multiplier was developed based on the data reported by Hafez (1984).

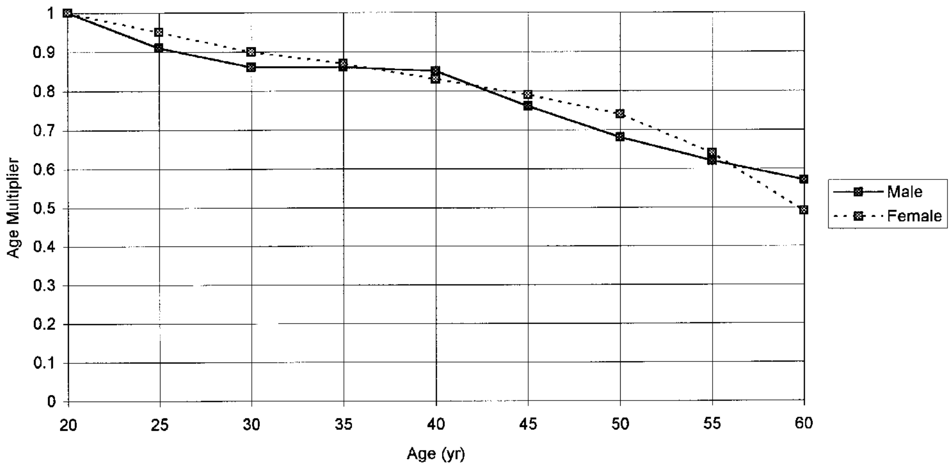

Figure 9. Age multiplier.

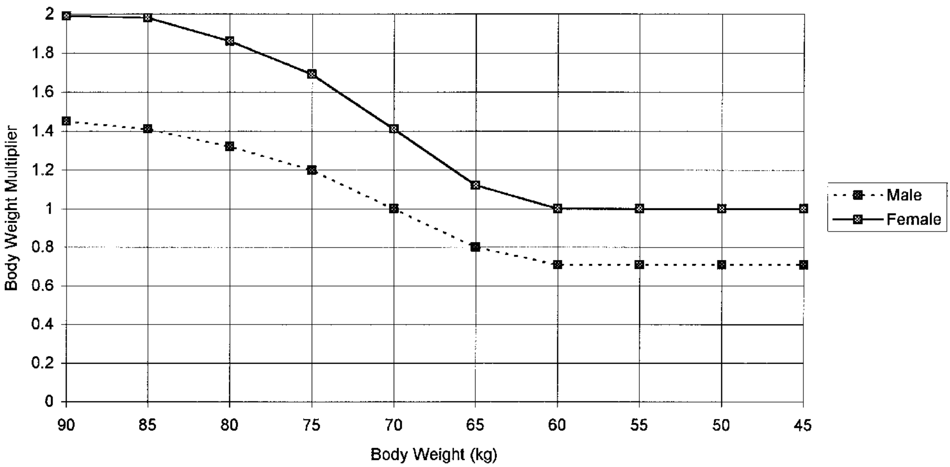

Figure 10. Body weight multiplier.

2.1.2. *Testing:* The lifting capacity obtained on the basis of psychophysical modelling was compared to the NIOSH lifting limits (Waters *et al.* 1993, Snook and Ciriello 1991, Ayoub *et al.* 1978). The following can be deduced about this comparative study:

(1) The lifting capacity predicted from the comprehensive lifting model (CLM) are generally within the 75% female and 99% male population limits of the Snook and Ciriello (1991) data.
(2) The lifting capacity predicted from the proposed CLM are comparable to data reported by Ayoub *et al.* (1978) at 2 times/min. At frequencies equal to 4 times/min or higher, the lifting capacity was only comparable to lifts that start at table height (76 cm above the floor).

(3) The lifting capacity data based on the CLM are equal to or less than the 1991 NIOSH limits except for: (a) the high frequency of 12 times/min (slight differences are observed at 8 times/min), and (b) the vertical distance at origin of lift below 76 cm above the floor. These differences in results are expected since NIOSH made use of physiological data in the high frequency range and biomechanical and physiological criteria for *V* values below 76 cm (Waters *et al*. 1993).

Testing the comprehensive lifting model developed in the first stage suggests that the vertical distance (*V*) multiplier should be evaluated for lifts that are initiated below 75 cm from physiological and biomechanical viewpoints. This is also applicable to very high frequencies of lift ($\geqslant$8 times/min).

2.2. *Second-stage model development and testing*

2.2.1. *Physiological considerations:* Since the physiological approach is the limiting factor to continuous lifting tasks at frequencies higher than 4 times/min (Genaidy 1983, Karwowski and Yates 1986, Waters *et al*. 1993), the data generated by Asfour *et al*. (1991b) was used to test the psychophysical task duration multiplier developed in the first stage of model formulation. As expected, it was found that the physiological multipliers were markedly lower than those based on the psychophysical approach. Thus, the task duration multiplier was based on the physiological approach instead of psychophysical criteria. Following this, the results of Asfour *et al*. (1991a,b) were also used to establish the upper limits for high frequencies of lift (table 1).

Energy expenditure corresponding to the 50% lifting capacity limits were predicted using Garg's models (Waters *et al*. 1993) and were compared against physiological fatigue limits generated by Asfour *et al*. (1991b). Physiological fatigue limits were mainly exceeded for the floor-to-knuckle height of lift for both males and females. This confirms the conclusions drawn from the first-stage of lifting capacity testing that the vertical distance (*V*) parameter should be examined in the floor-to-knuckle range. Moreover, the physiological fatigue limits were exceeded for frequencies equal to or greater than 8 times/min at the floor to knuckle height of lift. Thus, a modified *V* multiplier was formulated. The numerical values of the *V* multiplier were compared against the respective 1991 NIOSH multiplier. The discounting factors of *V* multiplier are more conservative than those adopted in the

Table 1. Maximum frequency based on a population percentage lasting up to a certain task duration.

Task duration (h)	Maximum frequency (times/min)	Population percentage
1	16	>75
2	16	>75
3	14	>75
4	14	>75
5	12	>75
6	10	>50
7	10	>50
8	10	>50

1991 NIOSH lifting equation. This could be primarily attributed to the fact that the curve established in this study was based on physiological data that was not used by NIOSH.

2.2.2. *Biomechanical considerations:* Age and body weight multipliers were developed using biomechanical data reported by Genaidy *et al.* (1993). The psychophysically-developed base weights were tested using benchmarks established by Tichauer (1978). The results clearly indicated that psychophysical data overestimates human abilities from a biomechanical standpoint. This is consistent with the hypothesis formulated and tested by Karwowski (1983) and by Karwowski and Ayoub (1984). New base weights that satisfy the Tichauer biomechanical benchmark are significantly lower than those based on psychophysical criteria.

3. Evaluation of manual lifting tasks

3.1. *Development of lifting indices*

Two types of indices can be used to evaluate manual lifting tasks using the proposed comprehensive lifting model. These indices are: (1) the relative lifting safety index (RLSI), and (2) the personal lifting safety index (PLSI). The RLSI can be used to evaluate a lifting task for a group of workers, while the PLSI assesses a lifting task for an individual worker. For RLSI, the lifting capacity is a function of task and environmental parameters. An RLSI value can be computed for males, females or both. For PLSI, the lifting capacity is a function of personal, task and environmental conditions.

The RLSI/PLSI indices can be computed as follows:

(1) determine the amount of weight lifted on the job;
(2) determine values of personal, task and environmental parameters and those for corresponding discounting factors;
(3) divide weight lifted on the job by the product of discounting factors. This will yield a base weight that can be used to determine the percentage of worker population; and
(4) divide obtained population percentage by 10, then subtract calculated value from 10. As such RLSI or PLSI can be translated into a score ranging from 0 to 10. The higher the score, the less safe the manual lifting job.

The RLSI/PLSI was transformed into a 0–10 scale to assist practitioners, especially those with limited backgrounds in ergonomics, in the interpretation of the results. The linguistic descriptors of Borg's scale (1982) might be used to interpret the obtained numerical scores:

0	
0·5	very very safe
1	very safe
2	safe
3	
4	somewhat unsafe
5	unsafe
6	

7 very unsafe
8
9
10 very very unsafe

3.2. *Examples*

The following hypothetical examples will illustrate the use of both RLSI and PLSI indices in lifting task evaluations. The results of both examples are summarized in table 2.

3.2.1. *Example 1:* The first example deals with a 50-year-old, 70 kg male employee who is expected to handle a 5 kg load under the following task and environmental conditions: (1) horizontal distance $H = 50$ cm; (2) vertical distance $V = 70$ cm; (3) vertical travel distance $D = 55$ cm; (4) frequency $F = 2$ times/min; (5) task duration $TD = 2$ h; (6) twisting angle $TA = 45°$; (7) poor quality handles, *C*; (8) heat stress $HS = 27°$ WBGT. This employee is supposed to return to work after regaining his

Table 2. Application examples for lifting indices.

Example	Type of variable	Level of variable	Discounting multiplier	Base weight	Population percentage
1	H	50 cm	0·68	23·25 kg	57
	V	70 cm	0·98		
	D	55 cm	0·84		
	F	2 times/min	0·89		
	TD	2 h	0·76		
	T	45°	0·89		
	C	poor	0·925		
	HS	27° WBGT	1·0		
	AG	50 years	0·69		
	BW	70 kg	1·0		
2	H	50 cm	0·68	18·23 kg	73
	V	70 cm	0·98		
	D	55 cm	0·84		
	F	2 times/min	0·89		
	TD	2 h	0·76		
	T	45°	0·89		
	C	poor	0·925		
	HS	27° WBGT	1·0		
	AG	35 years	0·88		
	BW	70 kg	1·0		

Note.
H: horizontal distance away from the body with respect to the mid-point between the ankles;
V: vertical distance from the floor to the hands at the origin of lift;
D: vertical travel distance of the hands between origin and destination of lift;
F: lifting frequency;
TD: task duration;
T: twisting angle;
C: coupling factor;
HS: heat stress;
AG: age;
BW: body weight.

physical work capacity during a rigorous rehabilitation programme. Is 5 kg a heavy load for him to handle?

In the first example, 5 kg will be considered to be the lifting capacity. The discounting factors for various parameters will be determined from figures 1 to 10. The base weight will be computed as the ratio of lifting capacity and product of discounting multipliers. Then, the population percentage corresponding to the base weight will be determined from figure 8.

The following values represent the discounting factors for various personal, task and environmental variables:

(1) *H* = 0·68 (figure 1);
(2) *V* = 0·98 (figure 2);
(3) *D* = 0·84 (figure 3);
(4) *F* = 0·89 (figure 4);
(5) *TD* = 0·76 (figure 5);
(6) *T* = 0·89 (figure 6);
(7) *C* = 0·925 (see § 2.1.1);
(8) *HS* = 1·0 (figure 7);
(9) Age = 0·69 (figure 9);
(10) Body weight = 1·0 (figure 10).

The base weight for a male worker under these conditions will be equal to the outcome of $[5/(0{\cdot}68 \times 0{\cdot}98 \times 0{\cdot}84 \times 0{\cdot}89 \times 0{\cdot}76 \times 0{\cdot}89 \times 0{\cdot}925 \times 1{\cdot}0 \times 0{\cdot}69 \times 1{\cdot}0)]$, which is 23·25 kg. This base weight is equivalent to the maximum load acceptable to 57% of the worker population (figure 8). Dividing 57 by 10 and subtracting the obtained value from 10 will yield a PLSI score of 4·3 out of 10. This value can be interpreted as 'somewhat unsafe' and administrative controls should be instituted.

3.2.2. *Example 2:* Consider another situation where one would like to evaluate a lifting job for a group of male workers. Assume: (1) the aforementioned task and environmental conditions; (2) average age of 35 years and average body weight of 70 kg. All discounting multipliers will be the same as in the first example, except for the age multiplier which is 0·88 for a 35 years age group.

The base weight will be equal to the outcome of $[5/(0{\cdot}68 \times 0{\cdot}98 \times 0{\cdot}84 \times 0{\cdot}89 \times 0{\cdot}76 \times 0{\cdot}89 \times 0{\cdot}925 \times 1{\cdot}0 \times 0{\cdot}88 \times 1{\cdot}0)]$, which is 18·23 kg. This base weight is equivalent to the maximum load acceptable to 73% of the worker population (figure 8). Dividing 73 by 10, and subtracting the obtained value from 10 will result in an RLSI of 2·7 out of 10. If all male workers do not suffer from previous medical problems and are in good fitness conditions, no action is required in the second example.

4. Conclusions

In this study, a comprehensive lifting model (CLM) for evaluation and design of manual tasks was developed in two stages. In the first stage, the model was built using the available psychophysical data related to human capacity in manual lifting tasks. In the second stage, discounting factors of various model variables were tested and adjusted using the available physiological and biomechanical data.

A subsequent paper (Shoaf *et al.* 1997) presents comprehensive models for evaluation and design of the lowering, carrying, pushing, pulling and holding activities.

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