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Development of a safety index for manual lifting tasks

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The concept of a safety index (SI) for assigning a worker to a particular manual lifting task is developed, and a simple formula for its calculation is presented. The proposed index is based upon the combined measure of acceptability of the biomechanical and physiological stress responses of the worker to a lifting task. Individual capacity norms, as opposed to the norms usually given based on population percentiles, are also defined. Numerical examples are given to illustrate the SI approach.

Keywords: Safety, manual handling, biomechanical stress

Introduction

Biomechanical, physiological and psychophysical criteria have been broadly used in the past to assess human capacities to perform manual materials handling tasks. However, limits computed by use of these criteria differ significantly with respect to the weights which may be lifted safely (Ayoub, 1982; Champion, 1983; Mital, 1983a). To date, most of the proposed limits are based on a single criterion and consider only a single stress response of the worker to a lifting task.

The majority of investigations dealing with manual lifting have ignored the effects of multiple stressors imposed upon the human operator. There are only a few exceptions in the literature (Freivalds *et al*, 1984; Mital, 1984; Mital *et al*, 1984). Human performance, however, depends on the intensity of physical load with respect to several different responses, e g, responses by the musculoskeletal, cardio-pulmonary, nervous and hormonal systems (Weiner, 1982). It is important, therefore, not only to quantify individual responses, but also to investigate their combined effect on work performance.

Recently, Karwowski and Ayoub (1984) proposed a new approach to determine the maximum acceptable weights of lift based on the combined effect of biomechanical and physiological stresses. In this paper, the combined stress effect is used to develop a general index of safety that can be associated with a given worker/job assignment. Fuzzy set theory (Zadeh, 1965) forms the basis of the proposed safety index. It is believed that such an index will be useful in evaluating manual lifting jobs in industry, and will contribute to the reduction of over-exertion injuries.

Background

The design criteria for establishing lifting capacity norms should take into account both potential risk of injury as well as work efficiency (Garg and Ayoub, 1980). Unfortunately, the load recommendations based on (say) the 10th percentile of the population, though considered safe for 90% of the population, are not desirable since the work efficiency of some workers is significantly impaired. On the other hand, the use of load limits acceptable to a small part of the population (90th percentile, say) is likely to result in injuries to weaker workers. The optimal solution, therefore, should provide for a significant reduction in the risk of injury as well as reasonable levels of work efficiency. Also, since human capabilities, characteristics (static and dynamic strength, aerobic capacity, sex, experience, etc) and responses to a task differ widely, each case of manual lifting should be considered individually and independently. This will permit a more reliable assessment of the individual's safety factor related to a particular lifting task, based on acceptability measures.

The concept of 'acceptability' in manual lifting is vague since the class of maximum 'acceptable weights' does not possess clear boundaries which separate those weights belonging to that class from those that do not belong (Karwowski, 1983). This kind of imprecision can be equated with fuzziness, where transition from membership to non-membership is gradual, rather than abrupt. A statement that a certain weight is acceptable to 50% of the population gives some information about the physical characteristics of the population in relation to the individual's ability to lift it safely. However, at the 50th percentile of the population, a given weight may be more 'acceptable' to some workers and less 'acceptable' to others. Therefore, one may identify the degrees of acceptability of the weight lifted with respect to a chosen criterion.

According to Weiner (1982), a degree of stress provides a measure on which the standards of general acceptability may be based. Also, such standards can be expressed in terms of the corresponding external load. Karwowski *et al* (1984) outlined an operational model of the decision-making process for selecting the maximum acceptable weight of lift based

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on the psychophysical approach. A graphical representation of this model is shown in Fig. 1.

In view of the proposed concept, the worker's perception of an effort and the subjective norm of lifting task acceptability are the main components for determining how much load a person would lift under given conditions. The biomechanical and physiological stresses are combined into an integrated response under the measure of psychophysical stress. Furthermore, according to the above model, the adjustments of the load lifted are aimed at minimising the difference between the perception of an effort and some subjective norm of an acceptable workload. At a certain level of similarity between the combined and psychophysical stresses, a decision is made and the current load lifted is selected as the maximum acceptable one. The details of the mathematical structure of the above model are given by Karwowski and Ayoub (1984) and Karwowski *et al* (1984).

Basic definitions

According to Zadeh (1973), a fuzzy subset A of a universe of discourse X is defined by a membership function $f_A : X \to [0,1]$ which associates with each element x of X a number $f_A(x)$ in the interval $[0,1]$, where $f_A(x)$ represents the grade of membership of x in A. Formally, A can be written as:

$$A = \{x, f_A(x) \mid x \in X\} \quad \ldots (1)$$

The support of A is the set of points in x at which $f_A(x)$ is positive. An α-level set of A is a non-fuzzy set denoted by $A\alpha$ which contains all elements of X whose grade of membership in A is greater than or equal to α. A is called normal if there is x such that $f_A(x) = 1$.

To simplify the notation, a fuzzy subset A with discrete membership function can be expressed as follows:

$$A = f_1/x_1 + f_2/x_2 + f_3/x_3 + \ldots + f_n/x_n \quad \ldots (2)$$

where f_i, $i = 1, 2, 3, \ldots n$, is the grade of membership of x in A, and

$$X = x_1 + x_2 + x_3 \ldots + x_n \quad \ldots (3)$$

X is the universe of discourse, where + denotes union rather than the arithmetic sum.

For the given fuzzy subsets A and B one can perform basic operations as follows:

Complement: $\bar{A} \Longleftrightarrow f_{\bar{A}} = 1 - f_A$ ... (4)

Union of two fuzzy subsets A and B, denoted $A \cup B$:

$$A \cup B \Longleftrightarrow f_{A \cup B} = f_A \vee f_B \quad \ldots (5)$$

Intersection of two fuzzy subsets, denoted $A \cap B$:

$$A \cap B \Longleftrightarrow f_{A \cap B} = f_A \wedge f_B \quad \ldots (6)$$

where: V and Λ denote MAX and MIN operators, respectively.

Product of A and B:

$$AxB \Longleftrightarrow f_{AxB} = f_A f_B \quad \ldots (7)$$

Concentration of A:

$$CON(A) = A^2 \Longleftrightarrow CON(f_A) = f_A^2 \quad \ldots (8)$$

Dilation of A:

$$DIL(A) = A^{0 \cdot 5} \Longleftrightarrow DIL(f_A) = f_A^{0 \cdot 5} \quad \ldots (9)$$

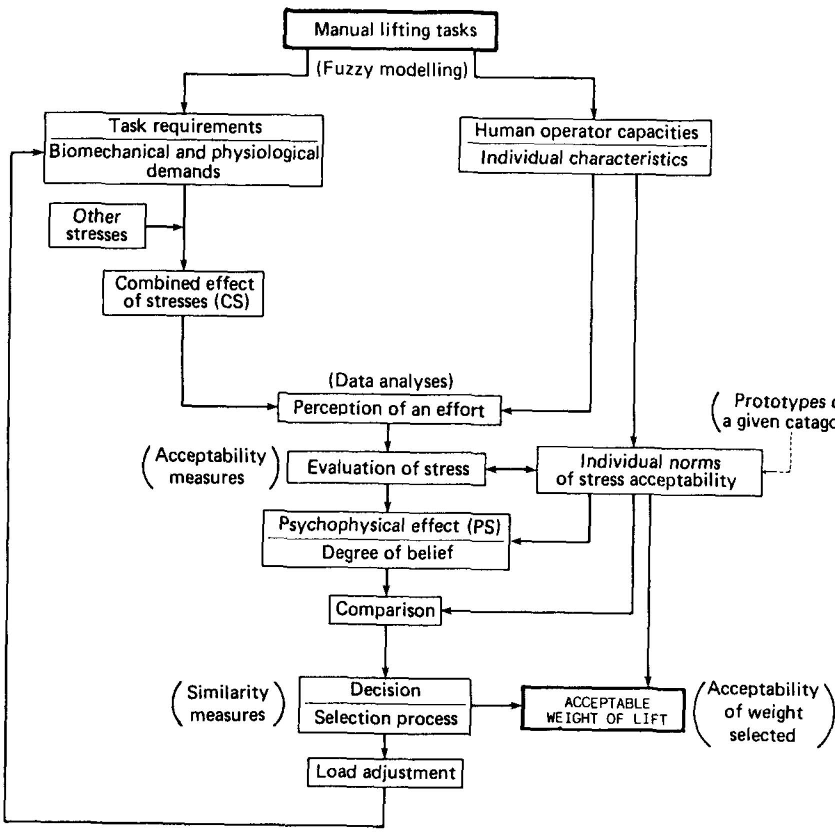

Fig. 1 Fuzzy model for selecting the maximum acceptable weight of lift based on the psychophysical criterion (after Karwowski *et al*, 1984)

Fuzziness and acceptability of weight lifted

Let us consider a universal set $X = \{x\}$ as a collection of possible weights that could be lifted by a worker under certain job conditions. The fuzzy subset A in X, representing the 'acceptable weights of lift', can be defined as a set of ordered pairs as follows:

$$A = \{(x, f_A(x)) \mid x \in X\} \qquad \ldots (10)$$

where $f_A(x)$ is a membership function from X to a set M indicating the grade of membership of x in the set A. It is assumed that M is in the closed continuous interval $[0,1]$, with 0 and 1 representing the lowest and the highest grades of membership, respectively. Thus, a fuzzy subset A of acceptable weights of lift is defined by associating with each weight, x, a grade between 0 and 1.

For example, if the weights to be lifted under given conditions are 10, 20, 30, 35, 40 and 50 kg, then the 'acceptable weights' from the safety viewpoint could be assessed by a practitioner in the field as follows:

$$A = ((10, 1{\cdot}0), (20, 0{\cdot}9), (30, 0{\cdot}8), (35, 0{\cdot}65), (40, 0{\cdot}5), (50, 0{\cdot}3)) \qquad \ldots (11)$$

In the above case, the grades of membership (acceptability) are subjective and are relative to the practitioner's perception of the possible risks of injury with respect to the weight lifted. However, the fuzziness in the concept of acceptability can be treated in a logical manner if the grades of membership are determined through objective experimentation instead of relying on their implicit definition.

For example, the fuzzy set A could be defined by some empirical membership function, such as shown in Fig. 2, and expressed mathematically as follows:

$$f_A(x) = \begin{cases} 1 & \text{, for } 0 < x \leqslant 5 \\ 1 - \frac{x}{48} & \text{, for } 5 < x < 48 \\ 0 & \text{, for } x \geqslant 48 \end{cases} \qquad \ldots (12)$$

The 'acceptable weight' of lift is represented here by the following set:

$$A = ((5, 1{\cdot}0), (10, 0{\cdot}78), (20, 0{\cdot}5), (30, 0{\cdot}3), (40, 0{\cdot}15), (50, 0))$$

In fuzzy modelling of manual lifting activities the degrees of stress provide a criterion on which the standards of acceptability may be based. As mentioned earlier, such standards can be expressed in terms of the corresponding external workload. The measures of acceptability can then be associated with the membership functions describing the degrees to which the biomechanical and physiological stresses are acceptable to the human operator.

It has been established that the combined effect of biomechanical and physiological stresses in lifting tasks have a similar effect on human operator performance as that found when using the psychophysical approach (Karwowski and Ayoub, 1984). Since the acceptability values based on both combined and psychophysical responses are close to one another at both low (see Fig. 3 a, b) and high lifting frequencies (see Fig. 3 c, d), it is assumed here that the acceptability measure of the load lifted can be based on the integrated effect of biomechanical and physiological stresses.

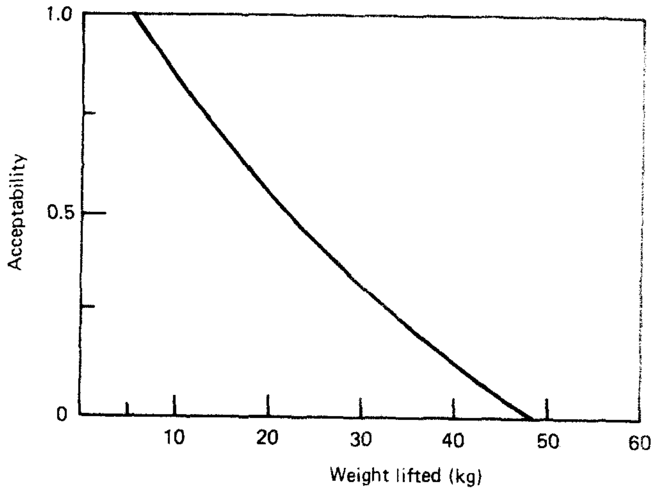

Fig. 2 Acceptable weight of lift as the fuzzy category

Furthermore, such acceptability measures, which relate the actual stress responses of human operators to their individual capacities, are equated with a safety index for the operator/job assignment.

The concept of a safety index

As discussed above, the value of a safety index for a particular lifting task should be based on the acceptability measure of the combined effect of biomechanical and physiological stress responses. For the biomechanical stress, such an acceptability measure can be based upon the magnitude of the compressive force at the L5/S1 disc. Since most of the serious back injuries due to manual lifting occur at the L5/S1 disc (Chaffin and Park, 1973), an estimate of compressive forces at the L5/S1 disc provides an indication of potentially injurious stresses in the low-back while lifting loads (Tichauer, 1971; Garg and Herrin, 1979).

Regarding the assessment of physiological stresses, the acceptability measure can be expressed in terms of the oxygen consumption rate, which is one of the most direct and accurate physiological measures of lifting task demands. Rodgers (1978) stated that the metabolic demand should be among the factors considered when developing safety standards for manual handling tasks. The physiological requirements can also be related to the individual's maximal aerobic capacity. Mital (1983b) and Mital *et al* (1984) have proposed an average metabolic energy expenditure limit of about 28% of VO_2 max (approximately 0·76 litre/min of oxygen for males, and 0·52 litre/min of oxygen for females).

The acceptability measures for the biomechanical and the physiological stresses should be based upon some widely accepted reference values. In the case of the former, such a reference is the maximum amount of compressive force on the L5/S1 disc that is considered 'safe'. Although many studies have investigated this issue (e g, Morris *et al*, 1961; Ekholm *et al*, 1982), a standard for the compressive loads has not been clearly established. Perey (1957), based on autopsy specimens, revealed the breaking point of the system vertebrae-disc-vertebrae to be 5003 – 10791 N (mean = 7651 N) for males under 40 years old, and to be

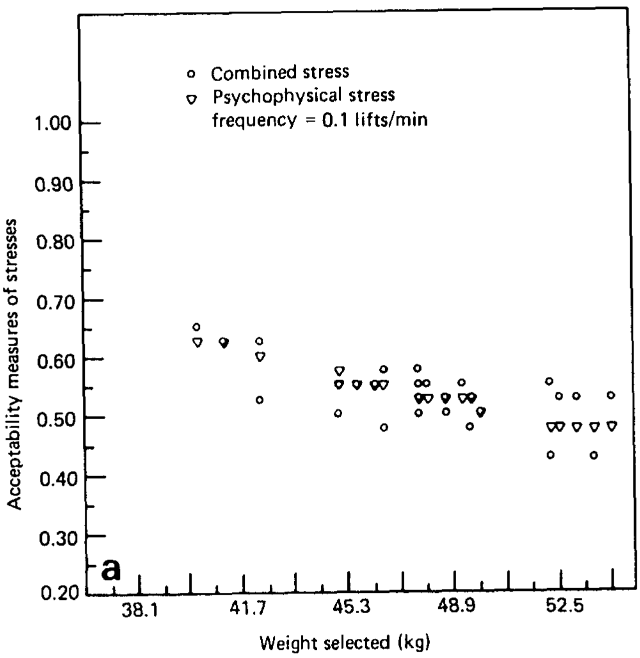

Fig. 3a Acceptability of the combined and psychophysical stresses, frequency = 0·1 lifts/min (Karwowski, 1982)

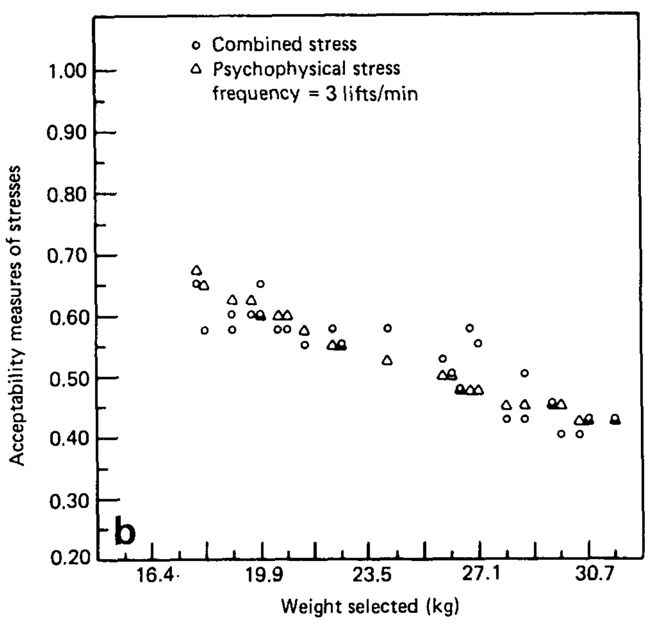

Fig. 3b Acceptability of the combined and psychophysical stresses, frequency = 3 lifts/min (Karwowski, 1982)

2845 – 5199 N (mean = 4169 N) for the group over 60 years old. These results were further reinforced by Schultz (1974). Karwowski *et al* (1984) were able to derive the reference values for the maximum compression on the L5/S1 disc by using the concept of minimising the differences between acceptability measures of the combined and the psychophysical stress responses to lifting tasks performed by college students. These results were further validated by Karwowski and Mital (1984) using male industrial workers lifting at rates of 1, 4, 8 and 12 lifts per minute.

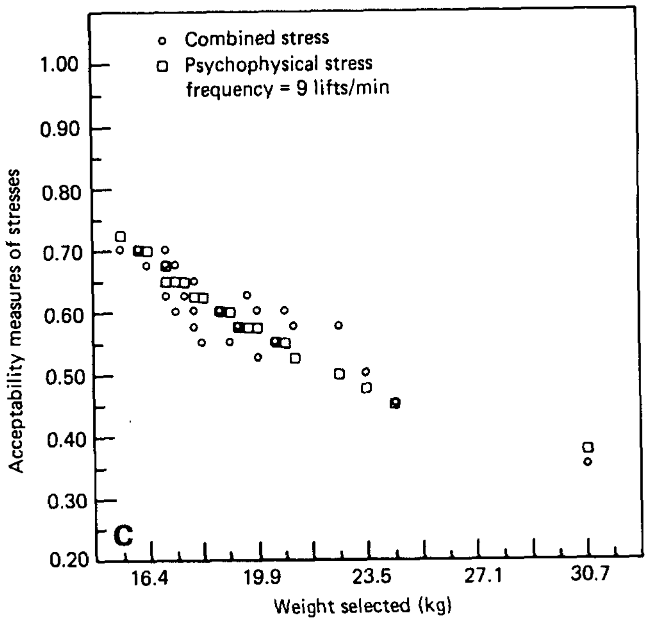

Fig. 3c Acceptability of the combined and psychophysical stresses, frequency = 9 lifts/min (Karwowski, 1982)

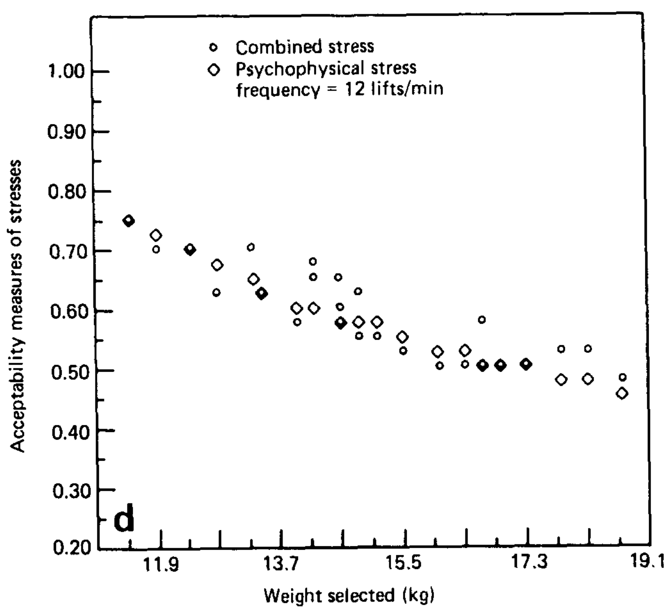

Fig. 3d Acceptability of the combined and psychophysical stresses, frequency = 12 lifts/min (Karwowski, 1982)

The reference values for both the biomechanical and the physiological stress, reported by Karwowski and Mital (1984), were used to define the overall safety index (Table 1). The level of safety associated with a worker/job assignment is expressed as the product of two components: the first component is the ratio of predicted compression on the L5/S1 disc to the reference value 'B(f)' for the biomechanical stress; the second component is the exponent of the ratio of the oxygen consumption (predicted or measured) to the reference value 'H(f)' for the physiological stress (Karwowski and Ayoub, 1984).

Table 1: Reference points for assessment of biomechanical and physiological stresses

Frequency of lift (lifts/min)	Reference points		
	B(f) [N]	H(f) [1VO$_2$/min]	K
1	4300	0·8	0·3
4	4200	0·8	0·3
8	3900	1·0	0·4
12	3900	1·0	0·4

Such a safety index (SI) can be written as follows:

$$SI = [F(x)/B(f)] * [exp(K*((H(f) - V(x))/H(f)))] \quad \ldots (13)$$

where x is weight of the load, f is the lifting frequency, K is a constant (see Table 1), $F(x)$ is the predicted compressive force on the L5/S1 disc, and $V(x)$ is the oxygen consumption due to lifting load x at a certain frequency f. This SI can be used as the preliminary tool to determine how safe a certain lifting job/worker assignment would be over an 8-hour shift.

In cases where the actual value of either the predicted compression or the oxygen uptake is less than the corresponding reference value, the relevant component of SI becomes 1·0, and Eqn (3) is reduced to a single component. When both responses – biomechanical and physiological – are less than the corresponding reference values, the SI is also equal to 1·0. This indicates that the demands of the lifting job under consideration are not likely to exceed the capacity of the worker.

As mentioned earlier, values of $F(x)$ and $V(x)$ could be either predicted or measured directly. The proposed safety index, in its present form, is limited to males lifting from the floor to a height of approximately 80 cm. This is a direct consequence of applying El-Bassoussi's (1974) biomechanical model for predicting maximum compressive forces $F(x)$ on the lower surface of the L5/S1 disc:

$$F(x) = 9{\cdot}81\ (390{\cdot}947 + (0{\cdot}260494\ (20{\cdot}32 + (\text{LENGTH}/2)) \cdot x)) \quad \ldots (14)$$

for squat lift (r = 0·736, standard error = 0·0258), and

$$F(x) = 9{\cdot}81\ (370{\cdot}047 + (0{\cdot}25836\ (20{\cdot}32 + (\text{LENGTH}/2)) \cdot x)) \quad \ldots (15)$$

for stoop lift (r = 0·746, standard error = 0·0289),

where maximum compressive force $F(x)$ is expressed in (N), weight lifted x in (kg), and LENGTH (cm) is the dimension in the sagittal plane.

In order to illustrate the practical application of the above concept, the experimental data from the study by Mital *et al* (1984) were used. SI values were calculated for several weights that were lifted at four different rates: 1, 4, 8 and 12 lifts per minute (Table 2).

Example 1

Packages (square boxes of 45·7 cm in size, each weighing about 22·8 kg) are to be lifted vertically from the floor to a conveyor belt (located at approximately 80 cm height). Based on the total volume of the material to be handled, it is expected that the work will continue for about 8 hours while lifting at a frequency of four packages per minute. A young, healthy worker has been assigned to this job. Based on an approximately 15 min trial of actual lifting, the oxygen consumption of the worker was measured at 0·87 litre/min. This indicated that the physiological strain was rather low. It should be noticed here that the metabolic energy expenditure rate for this job could also be estimated, for example, from the physiological cost prediction models developed by Mital and Ayoub (1981). The predicted maximum compressive force on the low-back was about 6134 N, and significantly exceeded the reference value for the biomechanical stress at 4 lifts/min (4200 N).

The SI (Eqn 3) for this particular worker/job assignment was calculated to be 0·67. The specification, to ensure

Table 2: Calculation of safety indexes for the worker/job assignments

Frequency (lifts/min)	Box size (cm)	Weight of load (kg) to be lifted for an 8-hour shift	Predicted compressive force (N)	Oxygen consumption (litres/min)	Safety index (SI)	Individual lifting capacity norm (kg) based on safety index
1	30·5	30·6	6611·4	0·77	0·6504	19·0
		27·9	6364·2	0·62	0·6756	18·9
4	30·5	36·0	6884·9	1·22	0·5211	18·8
	45·7	22·8	6133·9	0·87	0·6669	15·2
8	30·5	14·7	4968·9	0·98	0·7848	11·6
		26·6	6034·8	1·38	0·5551	14·8
12	30·5	13·2	4826·3	1·20	0·7459	9·8
		21·6	5583·5	2·10	0·4489	9·7

safe handling, is given in Table 2. The necessary amount of reduction in the weight can be determined by multiplying the actual load being lifted by the SI. In this example, the load should be reduced to approximately 15·2 kg (22·8 * 0·67) which corresponds to the lifting capacity of the worker for an 8-hour shift. In general such safe limits, or individual lifting capacity norms (ILCN), can be determined as follows:

$$ILCN = SI * x \text{ (kg)} \qquad \ldots (16)$$

Example 2

A worker is required to stack regularly shaped small containers weighing 21·6 kg on a pallet. The containers arrive at the operator's feet by way of a gravity chute. The pallet is located on the floor and the containers must be stacked six high (approximately table height) and two deep. The worker is expected to load one pallet per minute; that is, perform 12 lifts/min. While performing the job, the worker has been showing signs of fatigue evidenced by a high oxygen uptake rate of 2·1 litres/min. He is 35 years old and appears to be in good health. This worker has been employed with the company for the past 10 years and has held jobs in the past which required lifting similar loads, although at a lower frequency, with no obvious problems.

The predicted maximum compressive force on the lower back is 5583·2 N, exceeding by 30% that of the reference point for the biomechanical stress of 3900 N. The calculated SI value is 0·45, indicating that if such a high lifting frequency is to be maintained, the contents of the containers should be altered to the level of ILCN (see Table 2) so that they weigh only about 9·0 kg (assuming 0·7 kg weight of the container).

Discussion

Comparison of the calculated ILCN values of Table 2 with recommended maximum weights acceptable to male industrial workers shows remarkable similarities between corresponding values of weights over the full range of lifting frequencies. For instance, the recommended ILCNs for lifting once per minute are very close to the maximum acceptable weights of 19 kg (SD = 5·2 kg) reported by Kroemer (1983), of about 20 kg, for similar conditions suggested as the 'action limit' in the NIOSH Guide (NIOSH, 1981, p 126), and of 20·34 kg (SD = 4·55 kg) reported by Mital (1983b). Further, the ILCN values, which are based on the combined stress responses of the worker to a lifting task, compare well with the verified psychophysical norms of 15·42 kg (SD = 4·52 kg), 14·99 kg (SD = 5·34 kg), and 10·57 kg (SD = 3·5 kg) for lifting rates of 4, 8, 12 lifts/min respectively (Mital *et al*, 1984).

Based on the SI values, certain actions for lifting loads could be proposed. For example, a job requiring continuous lifting of 26·6 kg loads at the rate of 8 lifts/min has a SI of 0·555 (Table 2). For safety, this task should be altered by reducing the weight to be lifted and/or lowering the frequency of lift. It should be remembered, however, that lowering the weight of load is much more important from the safety viewpoint than lowering the frequency.

Capacity norms based on the SI are superior to the simplified design criteria which require no knowledge of biomechanics, psychophysics or metabolic endurance, but rely on the given tables (Letbetter, 1982). Although the proposed safety index is simple, it does require some understanding of basic principles of the biomechanical and physiological requirements of manual lifting tasks. However, this knowledge can be beneficial to potential users. It is strongly believed that the use of any criterion without proper knowledge and understanding could be damaging to the worker's health and well-being.

Conclusions

The safety index proposed in this paper is based upon the combined effect of biomechanical and physiological stress responses of a worker to a particular job. As such, it represents a departure from the conventional approach of determining lifting capacity norms with respect to a specific population percentile. More research is needed to develop such safety measures which could be used as a basis for establishing lifting capacities for a given worker/job assignment. Safety indices for the whole spectrum of lifting frequencies, as well as different box sizes and lifting heights, for both male and female populations, should be developed. In order to increase the reliability of the SI, it should be correlated with multiple response prediction models. Further studies in this area are ongoing.

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