

Fuzzy modelling of stresses in manual lifting tasks

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A new approach, based on the theory of fuzzy sets and systems, was proposed to assess the acceptability of stresses involved in manual lifting tasks. Nine male subjects participated in a laboratory lifting experiment. A total of 108 data points (9 subjects \times 4 levels of frequency \times 3 replications) were collected. The maximum acceptable weights of lift were determined using the psychophysical methodology. Metabolic energy expenditure and heart rates were also measured. A hypothesis, stating that the combined effect of biomechanical and physiological stresses leads to an overall measure of lifting task acceptability as expressed by the psychophysical stress, was suggested and evaluated. Conditions were found for which the acceptability measures of the combined and the psychophysical stresses were close to one another. A concept of safety index for a particular weight of load lifted was also proposed.

1. Introduction

Successful application of the theory of fuzzy sets (Zadeh 1965) in the modelling of man-centred systems has attracted little attention from researchers in the area of human factors. This is unfortunate since inexactness and imprecision due to complexity are naturally attached to most of the problems under investigation. Some of the attempts to apply fuzzy sets in ergonomics research are represented by the studies on visual inspection tasks (Malvache and Willayes 1979), analysis of memorizing and forgetting (Kokawa *et al.* 1975), modelling of man-machine systems (Grobelyny and Nowakowski 1980), mental stress quantification (Mital and Ulgen 1982) and studies on the interaction between stresses involved in manual lifting tasks (Karwowski 1982, 1983).

A complex system of the human-operator lifting task has been studied in the past using in general three different approaches: biomechanical, physiological and psychophysical, with the main emphasis on a single load imposed on the worker during the lifting action. In spite of several studies (Chaffin *et al.* 1977, Snook 1978, Ayoub 1978, Leeg and Myles 1981), the problem of determining the maximum acceptable weight of load that can be lifted safely remains unsolved. One of the difficulties in establishing universal capacity norms for industrial workers is the fact that most of the previous studies did not consider the combined effects of multiple stressors (Weiner 1982) due to multiple loads present when lifting.

This study introduces a new methodology to evaluate the acceptability criteria for the three major stress responses (stresses) involved in lifting activities. A fuzzy-sets-based model for the assessment of acceptability measures of the considered stresses is proposed.

A hypothesis, stating that a combination of the acceptability of biomechanical and physiological stresses leads to an overall measure of lifting task acceptability, as expressed by the psychophysical stress, was also evaluated. It was assumed that such a combination had a synergistic effect on the individual's lifting performance. The perception of this effect was reflected in a person's subjective judgement when selecting the maximum acceptable weight. The effects of other stresses were neglected.

2. The model

Advances in the theory of fuzzy sets made it possible to deal with complex and ill-defined, human-centred systems (Zadeh 1973). Imprecision due to complexity can be associated with the classes of objects with no sharp transition from membership to non-membership. Karwowski (1983) realized this concept when studying the interaction between stresses involved in manual lifting tasks.

A class of acceptable weights of lift does not possess clear boundaries. In other words, the boundaries which separate those weights which belong to that class from those which do not. This kind of imprecision can be equated with fuzziness. The criteria for acceptability of the load lifted can then be defined as fuzzy categories. Measures of acceptability are associated with membership functions, describing the degrees to which the biomechanical and physiological stresses are acceptable to the human operator.

3. Definitions

3.1. Definition of a fuzzy subset

Let us consider a universal set $X = \{x\}$ as a collection of all possible weights that could be selected during the psychophysical lifting experiment. A fuzzy subset A in X is a set of ordered pairs, defined as follows:

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

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

3.2. Acceptability criteria

A fuzzy subset B in X , named the maximum acceptable weight of lift (MAWL) from the biomechanical point of view, is defined as follows:

$$B = \{(x, f_B(x)) | x \in X\} \quad (2)$$

with membership function:

$$f_B(x) = \begin{cases} 1 & \text{for } F(x) \leq b, \\ b/F(x) & \text{for } F(x) > b. \end{cases} \quad (3)$$

b denotes a reference point, i.e. the largest value of the maximum compressive force $F(x)$ considered as 'safe'.

At present the reference value for biomechanical stress cannot be easily established. NIOSH (1981), in its *Work Practices Guide for Manual Lifting*, stated that jobs which

place more than 6380 N of compressive force on the lower back are hazardous to most workers, and that a level of 3430 N or lower should be considered as an upper limit. Ekholm *et al.* (1982) reported results of the previous studies and concluded that the discs of the lumbar spine can withstand compressive loads of about 2500–7650 N, in autopsy specimens.

For the purpose of this study, the relationship between reported low-back pain incidence rate and predicted maximum compressive force on the L5/S1 disc (NIOSH 1981) was analysed, and the reference values b were defined to be within a range from 2940 to 4900 N. These values corresponded to the level of 9.1–9.8 low-back pain incidence rate for 200 000 man-hours worked, and allowed the consideration of a broad spectrum of 'safe' limits, as discussed by Karwowski (1982).

A fuzzy subset H in X , called the MAWL from the metabolic energy expenditure rate standpoint, is a set:

$$H = \{x, f_H(x) | x \in X\} \quad (4)$$

with membership function:

$$f_H(x) = \begin{cases} 1 & \text{for } V(x) \leq h, \\ \exp(k(h - V(x))/h), & 0 < k < 1, \text{ for } V(x) > h. \end{cases} \quad (5)$$

The reference point h is the recommended value of oxygen uptake for an 8 hour long physical activity, and $V(x)$ denotes the actual oxygen consumption resulting from lifting load $\{x\}$.

Based on the results reported by Åstrand and Rodahl (1977), Rodgers (1978) and Garg and Saxena (1979), it was assumed that the value of h for high frequencies of lift corresponded to the recommended metabolic energy expenditure rate of 349 J/s (or 5 kcal/min). Therefore, h was set at 1 l of $\dot{V}O_2$ /min. In order to indicate stress at the frequencies of 0.1 and 3 lifts/min the value of 0.5 l of $\dot{V}O_2$ /min was used. This corresponded to the lower level of the physiological limit for the moderate work, as discussed by Karwowski (1982).

A fuzzy subset P in X , called the MAWL from the psychophysical point of view, is defined as a set:

$$P = \{x, f_p(x) | x \in X\} \quad (6)$$

with membership function:

$$f_p(x) = \begin{cases} 1 & \text{for } p(f) \geq x, \\ p(f)/x & \text{for } p(f) < x, \end{cases} \quad (7)$$

where $p(f)$ denotes a reference value (the most desirable value of load lifted considering both safety and efficiency of the task) for a particular frequency of lift f .

The points of reference $p(f)$ were based on the lifting capacity norms (Ayoub 1980) for the 10th percentile of the U.S. population. The points of reference were 25.30, 14.10, 11.25 and 8.45 kg for the frequencies of 0.1, 3, 9 and 12 lifts/min, respectively. These values were for lifting from floor to 0.76 m height, using a box size of 0.38 m in the midsagittal plane.

3.3. Combined effect

It was assumed in this study that the conjunction of the biomechanical and physiological stresses had a synergistic effect on the individual's performance when

lifting. From the fuzziness point of view such an effect implies that the acceptability measures of combined stress are lower (at each point x) than the acceptability of either biomechanical or physiological stresses, when considered alone. Koczy and Hajnal (1977) have shown that the algebraic product (as applied to fuzzy sets) has all the properties of the conjunction 'and'. Since this operation also satisfies the condition of synergy, the algebraic product was used to combine acceptability measures of the stresses into one category.

A fuzzy subset H in X , called the MAWL from the metabolic energy expenditure as a set:

$$C = \{x, f_c(x) | x \in X\} \quad (8)$$

with the membership function:

$$f_c(x) = f_B(x) f_H(x) \quad (9)$$

3.4. Evaluation of the hypothesis

To evaluate the hypothesis stated earlier, a fuzzy index of similarity between two fuzzy subsets C and P was applied. A dissimilarity measure (Dimitrov and Cuntchew 1977) was implemented with the formula for the similarity index (SI) between acceptabilities of the combined and psychophysical stresses.

The similarity index is defined as follows:

$$SI = 1 - \frac{\sum_j^n |f_c(x_j) - f_p(x_j)|}{n + \sum_j \min \{f_c(x_j), f_p(x_j)\}}, \quad (10)$$

where $j = 1, 2, \dots, n$.

Since the reference point b for the biomechanical stress was not explicitly known, it was proposed, as the first step in assessing the hypothesis, to evaluate under what conditions the distance between the fuzzy subsets C and P could be minimized. The idea of relative Hamming distance (Dubois and Prade 1980), given in the form of:

$$d(C, P) = \frac{1}{n} \sum_{j=1}^n |f_c(x_j) - f_p(x_j)| \quad (11)$$

was applied for this purpose.

Note that it is possible that for a given value of the minimized distance between C and P , the similarity index would not be sufficiently close to 1.0 (where 1.0 indicates that C and P are identical). The satisfactory value of SI depends upon the designer's requirements concerning implementation of the results.

A computer program was written to find the values for the reference point b and the constant k (see formula (5)) which minimized the relative Hamming distance between C and P . The complete enumeration of all values of b (from 2940 to 4900 N with a step size of 10 N) and k (from 0 to 1.0) was proposed.

4. Method and experimental procedure

To secure data for the evaluation of the stated hypothesis a psychophysical lifting experiment was carried out.

Nine male students participated in a laboratory study. An effort was made to stratify the sample, so it would represent the various segments of the population with

respect to height, weight, isometric strength and predicted maximal oxygen uptake. The paid subjects had had only minimal experience in the area of lifting. All subjects were in good physical condition, and had not suffered from any musculoskeletal or cardiovascular problems in the past. In order to eliminate the effect of learning on data collection, and to familiarize subjects with the lifting task, the subjects were trained. Characteristics of the subjects are given in table 1.

Table 1. Characteristics of the subjects.

	Range	Mean	S.D.
Age (years)	19-23	20.7	1.8
Weight (kg)	63.3-94.8	80.4	10.8
Height (cm)	168-186.4	178.5	5.6
Acromial height (cm)	133-152.1	143.7	6.0
Maximum aerobic capacity (ml/(kg min)) after training	39.1-56.5	46.6	6.1
Overall strength index (N) after training	3952-6913	5510	992

Four levels of lifting frequency: 0.1, 3, 9, and 12 lifts/min were used. The height of lift (from floor to 0.76 m height) was predetermined by the applicability of the biomechanical dynamic lifting model (Ayoub and El-Bassoussi 1976) used to assess the maximum compressive forces on the lower surface of L5/S1 disc. Although the subjects were allowed to utilize a natural (free) style of lift, the lifting techniques were classified into two categories: leg (squat) and stooped-back (stoop) lifts. This was done in order to satisfy the requirements of El-Bassoussi's model.

The subjects were asked to lift a square tote box, 0.38 m in length and 0.25 m high with handles on both sides. The handles were placed 0.20 m above the bottom of the box. The initial weight of the false-bottomed box was 31.75 kg (including the weight of an empty box equal to 5 kg).

Instructions given to the subjects were those devised by Snook (1978). The subjects were instructed to 'imagine that you are on piece work, getting paid for the number of lifts that you make, working a normal 8 hour shift that allows you to go home without feeling bushed. In other words, we want you to work as hard as you can without becoming tired, weakened, overheated or out of breath'. The subjects were encouraged to make as many adjustments as they felt were necessary by adding or subtracting small lead weights.

Each subject was given 40 min to decide on the load he was willing to lift for frequencies of 3, 9 and 12 lifts/min. The 2 hour period was used when lifting at the rate of one lift every 10 min (frequency of 0.1 lifts/min). The amount of time chosen for the very low frequency allowed the subject to make a choice based on the total of 12 lifts. After selecting a load, the subject was connected to the Beckman Metabolic Measurement Cart, using a mouth piece and nose clip. The subject was monitored for 8 min (for frequencies of 3, 9 and 12 lifts/min) while lifting the load selected without making any further adjustments. During the last 4 min of that period the oxygen uptake (STPD) was measured, and the average value of the four readings was recorded.

When lifting with the frequency of 0.1 lifts/min, the subject was given 35 min to lift the selected load. During the entire period the oxygen uptake was recorded with 1 min

intervals between the readings. The first lift in this case was done after 1 min; the second, third and fourth ones were performed after 11, 21 and 31 min, respectively. Since the time interval between two successive lifts was long enough for recovery to take place, the average value of all readings reflected the standing oxygen consumption plus the effect of four lifts.

5. Results and discussion

On the average, loads of 44.8, 29.3, 19.3 and 15.1 kg were selected by the subjects as the maximum acceptable weights of lift for the frequencies of 0.1, 3, 9 and 12 lifts/min, respectively. The average oxygen consumption rates resulting from lifting the selected loads were 0.43, 0.81, 1.32 and 1.44 l of O₂/min.

The results of the iterative procedure, used to identify the conditions for which the relative Hamming distance between the combined and psychophysical stresses was minimum, are summarized in table 2.

Table 2. Conditions for the developed model.

Frequency of lift (lifts/min)	Reference points for the stresses				Relative Hamming distance between <i>C</i> and <i>P</i>
	<i>b</i> (N)	<i>h</i> (l O ₂ /min)	<i>k</i>	<i>p</i> (<i>f</i>) (kg)	
0.1	4120	0.5	0.3	25.30	0.03105
3	3924	0.5	0.3	14.10	0.02685
9	3727	1.0	0.5	11.25	0.03300
12	3629	1.0	0.5	8.45	0.02948

A fuzzy measure of similarity between acceptability measures of the combined and the psychophysical stresses was then calculated (table 3). The values of similarity index were very close to 1.0, indicating that for the conditions of the model chosen above the fuzzy subsets *C* and *P* were close to one another. These fuzzy subsets could be treated, at least for practical purposes, as equal. The relationship between acceptability measures for the combined and the psychophysical stresses is depicted in figure 1.

The meaning and significance of the above results can be explained as follows. Assuming that one can measure acceptability of the stresses using the conditions proposed by the developed model (reference values for the evaluation of stresses), it is possible to assess what kind of overall stress would be likely to occur in a given lifting situation. This can be done by combining the acceptability measures of the biomechanical and the physiological stresses into one category.

Table 3. Similarity measures for the model.

Frequency of lift (lifts/min)	Similarity index
0.1	0.9795
3	0.9822
9	0.9790
12	0.9811

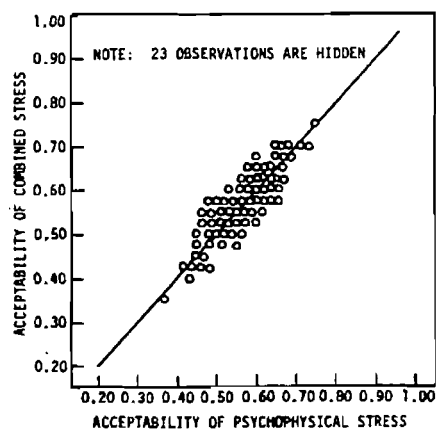


Figure 1. Acceptability of the combined stress versus acceptability of the psychophysical stress.

For example (Karwowski 1982), let us consider an individual lifting a load of 34 kg with a frequency of 3 lifts/min, using the squat lifting technique. The oxygen consumption rate (measured, but could be predicted) is equal to 0.886 l of O_2 /min. The maximum compressive force on the L5/S1 disc, as predicted by El-Bassoussi's model (El-Bassoussi 1974), equals 7497 N. The acceptability of the combined stress can then be calculated as an algebraic product of the acceptability measures of the physiological and biomechanical stresses. These are equal in this case to 0.793 and 0.523, respectively. The resulting value for the combined stress is 0.4147.

The hypothetical capacity norm for this individual could now be determined as the product of a load and its acceptability measure: $34 \text{ kg} \times 0.4147 = 14.10 \text{ kg}$. Such a norm would indicate the 'ideal' maximum acceptable weight a person could lift with a very low strain. The acceptability of the lifting task would be close to 1.0.

Therefore, one could consider the grade of membership for the combined stress as the indicator of acceptability of the lifting task, or the level of safety associated with it. In our example, the lifting task could be redesigned, by changing the load lifted and/or the task variables, to provide for a certain (desired) level of safety between 0.415 and 1.0.

The results of this study are of a preliminary nature, and further research will be needed to justify some of the assumptions proposed. It was suggested, based on the limited experimental data, that the overall assessment of the loads imposed on the human operator when lifting could be made by combining the acceptability measures of the involved stresses. It was shown that this could be done by applying the theory of fuzzy sets and systems. The proposed approach seems to be promising in the modelling of manual materials handling tasks, and does not have to be limited to lifting activities only.

Une nouvelle approche basée sur la théorie des ensembles flous et sur la théorie des systèmes est proposée pour évaluer l'acceptabilité des contraintes liées aux tâches de soulèvement manuel. Neuf sujets de sexe masculin ont participé à une expérience de soulèvement en laboratoire. Un total de 108 points de données (9 sujets \times 4 niveaux \times 3 répétitions) ont été recueillis. Les poids maximum acceptables pour le soulèvement ont été déterminés à l'aide d'une technique psychophysique. La dépense énergétique métabolique et les fréquences cardiaques ont également

été déterminées. On a éprouvé une hypothèse selon laquelle l'effet combiné des contraintes biomécaniques et physiologiques serait susceptible de fournir une évaluation globale de l'acceptabilité de la tâche de soulèvement telle qu'elle est exprimée par la contrainte psychophysique. On a pu établir les conditions dans lesquelles se produit le rapprochement entre les évaluations de l'acceptabilité et les contraintes psychophysiques. On a également pu proposer un indice de sécurité pour chacun des poids soulevés étudiés.

Ein neuer Ansatz zur Beurteilung der Zulässigkeit der Belastung beim manuellen Handhaben von Lasten wird auf der Grundlage der Theorie von unscharfen Mengen und Systemen vorgeschlagen. Neun männliche Versuchspersonen nehmen an Laboruntersuchungen des Handhabens von Lasten teil. Insgesamt wurden 108 Versuchsergebnisse (9 Versuchspersonen \times 4 Bewegungsfrequenzen \times 3 Wiederholungen) gewonnen. Das maximal zulässige Gewicht beim Heben wurde mit der psychophysikalischen Methode bestimmt. Gemessen wurde auch der Energieumsatz und die Herzschlagfrequenz. Aufgestellt und untersucht wurde die Hypothese, daß die kombinierte Auswirkung der biomechanischen und der physiologischen Belastungen zusammengefaßt zu einem Maß der Zulässigkeit eines Falles der Handhabung von Lasten führt, wie es als psychophysikalische Belastung zum Ausdruck kommt. Es wurden die Bedingungen gefunden, bei welchen sich die Zulässigkeitsmaße der kombinierten und der psychophysikalischen Belastung annäherten. Vorgeschlagen wurde auch ein Konzept für Sicherheitskoeffizienten bei submaximalen Lastgewichten.

手による持上げ作業に含まれるストレスの許容量を評価するために、ファジー集合、ファジー・システムの理論に基礎を置く新しい研究法を提起する。男性被験者9名が実験室での持上げ作業実験を行い、これより総計108のデータ（被験者9名 \times 持上げ頻度4レベル \times 繰返し3回）を得た。精神物理学的方法を用いて最大許容重量を決定した。代謝エネルギー消費量と心拍数も測定した。生体力学的なストレスと生理学的ストレスとの複合した影響が、精神物理学のストレスで表わされる持上げ作業の全許容値を導くという仮説が示唆され、評価された。複合ストレスと精神物理学のストレスの許容値が互いに近い値となる条件が見つけられた。ある重量の持上げ負荷に対する安全指数の概念が提案された。

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