Problems and solutions in manual materials handling: the state of the art

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For several decades manual materials handling has been a topic of interest in many fields of research. The reason for this interest is the devastating cost of and human suffering caused by injuries associated with MMH. Prevention and control of these injuries has been a concern shared by many researchers. In order to control the nature and extent of these injuries, limits must be established for MMH, especially lifting. This paper summarizes the variables affecting the ability to handle materials and the three basic approaches to determining capacities and limits for MMH: the biomechanical, the physiological, and the psychophysical approaches. The paper presents the various models developed in each of these approaches, together with a discussion of progress made and difficulties encountered in deriving capacity recommendations from each. Finally, the paper presents the latest recommendation on how these approaches can be integrated into a single comprehensive model for establishing lifting limits.

1. Introduction

For nearly four decades, manual materials handling (MMH) has been a major topic of interest to professionals from a number of disciplines, including engineering, ergonomics, physical therapy and rehabilitation, orthopaedic surgery, work physiology, and biomechanics. The primary reason for this interest is the devastating cost of and human suffering caused by the severity of MMH-related injuries. Prevention and control of such injuries is a global concern, shared by many researchers and organizations.

The research over the years focused on the establishment of acceptable handling limits using several different approaches and the application of ergonomic principles to job design, employee placement, and employee training. The reason for the extensive research effort is that MMH, particularly manual lifting, represents a major cause of injury to industrial workers and a significant cost to industry.

Back injury, particularly to the lower back, occurs with alarming frequency. Troup (1965) stated that in the United Kingdom, about 19% of all reported accidents affect the spine and trunk, and approximately 40% of back injuries result from lifting, and 33% are from twisting movements of the spine. More recent studies show that back injuries in industry are still a major source of lost time and compensation claims. Caillet (1981) estimated that 70 million Americans have suffered back injuries and that this number will increase by 7 million annually. Back injuries and disabling low back pain incidences are responsible for up to 25·5% of all worker compensation claims (Klein *et al.* 1984). According to Khalil *et al.* (1984), low back pain is the second largest pain problem, headaches being the first. Figure 1 summarizes the National Safety Council's MMH-related back injury and cost statistics from 1972 to 1984. Efforts to combat the injury problem of MMH have
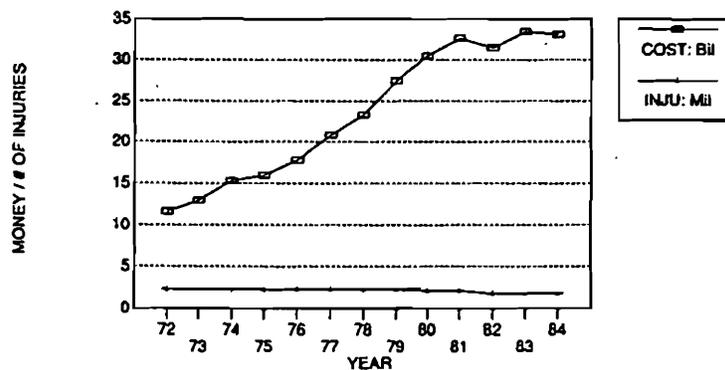
Figure 1. Work injury and cost statistics, by year (Ayoub and Mital 1989).

resulted in a variety of guidelines (NIOSH 1981, Davis and Stubbs 1980). In spite of these available guidelines, there is epidemiological evidence that the majority of injuries are being caused by overexertion (Holbrook *et al.* 1984). As a result a renewed effort for guidance and regulation to establish limits on MMH is under way in several countries (ILO 1988, HSC 1988, NIOSH 1990).

2. The MMH work system

A system may consist of people or physical parts or both. An ill-conceived and improperly organized system inevitably leads to inefficient system performance which must be tolerated by its human components—often at great cost, pain, and suffering—if the system is to remain operational (Ayoub and Mital 1989). A manual materials handling system is no exception. In order to design an efficient MMH system, it is critical that the effects of all its components on the capability of humans to adapt, or adjust, be clearly understood. Only when all cause and effect relationships become known, is it possible to design an orderly MMH system structure.

A handling system consists of four components: (*a*) worker; (*b*) task; (*c*) tools and equipment; and (*d*) environment. The ergonomic approach to MMH tasks focuses on three of these, necessitating a human–task–environment system. A generally accepted means of minimizing MMH-related injuries is that of designing MMH tasks so that the physical, physiological, and mental demands of such tasks are within the physical, physiological and mental capacities of the work force performing those tasks (figure 2). Therefore task design is dependent on the availability of data for worker capacities for MMH. The generation of such data is dependent on being able to identify the pertinent parameters of manual materials handling activities when using different approaches.

In order to determine safe limits for individuals and groups of individuals, it has been assumed that there is a relationship between an individual's lifting capacity and his or her injury potential. Therefore it has been essential to establish individual and population capacities for MMH. In order to establish such capacities, researchers have investigated the three system components and their characteristics which influence capacity of MMH.
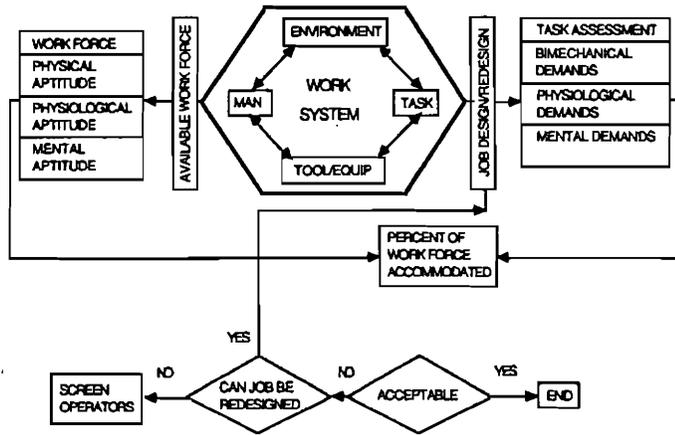
Figure 2. A general lifting model (modified from Ayoub *et al.* 1983).

2.1. *The worker as a system component*

While the effects of some worker characteristics which affect handling abilities are well known and have been found to be consistent, there exists both conflicting and contradictory information on other characteristics.

Table 1 shows a listing of the various worker characteristics (Chaffin and Ayoub 1975) and their relative importance by percentage as cited by various researchers (Herrin *et al.* 1974). While the research base supports the notion that all of these characteristics, singularly and collectively, determine a person's material handling capability, the research base is insufficient from which to derive specific quantitative information in several cases (Ayoub and Mital 1989).

2.2. *The task as a system component*

Elements which describe or define the MMH activity comprise the task component. Table 2 lists various characteristics that have been recognized as factors which contribute to the MMH hazard (Chaffin and Ayoub 1975). Some of these are related to the object being handled, such as shape, size, load distribution, and stability, while others, such as frequency, distance moved, duration, and workplace geometry,

Table 1. Worker characteristics cited as important by various researchers in determining personal risk of injury in MMH (Herrin *et al.* 1974).

Worker characteristic	Percentage of citations
Physical	38
Sensory	2
Motor	13
Psychomotor	3
Personality	6
Training and experience	8
Health status	30

describe the task itself. Three main approaches have been used by investigators to study task characteristics and their effects on workers' MMH capabilities. These design approaches will be discussed in a later section of the paper.

Table 2.   Task characteristics comprising the task component of the MMH system (Chaffin and Ayoub 1975).

Load	Measure of mass, force requirements, mass moment of inertia.
Dimensions	Measures of size and shape of the load.
Distribution of load	Measure of the location of the unit load c.g.
Couplings	Measures of simple devices used to aid in grasping the load.
Stability of load	Measures of constancy of the load c.g.
Workplace geometry	Measures of spatial properties of the task.
Frequency/duration/pace	Measures of the time dimensions of the handling task.
Complexity	Measures of compounding demands of the task.

2.3. *The environment as a system component*

The environment as an MMH system component can influence the ability to perform MMH tasks. Environmental characteristics include thermal factors such as temperature, humidity, and air velocity; other characteristics include noise, light, vibration, traction, and stability of the work platform. Of all of these environmental characteristics, only the thermal effects on MMH have been studied (Snook and Ciriello 1974, Hafez 1984).

The manual handling system is a complex work system that gives rise to interactions among its system components; these components, in turn, can have significant effects on handling limits. More research should address such interactions and their significance on capacity and possible safe limits.

3. The design approaches

For the development of a safe and permissible lifting capacity, three approaches have been discussed frequently. The first approach is the biomechanical approach, the second is the physiological approach, and the third is the psychophysical approach. Each of these approaches is discussed in some detail below.

3.1. *Biomechanical design approach*

The biomechanical design approach for MMH activities deals with force loadings on the musculoskeletal system as predictors of tissue tolerance and muscle sprains and strains (Garg and Herrin 1979). The primary objective of biomechanical studies of lifting has been the reduction of work-related injuries of the musculoskeletal system. Because of injury data available suggest that the back is a major area of concern, one approach has proposed that acceptable load limits be a function of back strength (Asmussen et al. 1965, Poulsen and Jorgensen 1971).

Although there is disagreement as to the cause of low back pain, the compressive force on the lumbar spine, especially on L5/S1 segment, has been accepted now as

one of the primary means of stress on the spine during MMH activities (Garg 1979). In the development of lifting limits, the compressive force has been used as a criterion, and a limit of 650 kg has been set for this criterion based on a study by Chaffin and Park (1973). This value was adopted by NIOSH (1981) for the maximum permissible limit (MPL). Data compiled from studies by Evans and Lissner (1959) and Sonada (1962) show large variation in the compressive strength of the L5/S1 segment. They reported that, in general, for males under 40 years of age, mean strength is approximately 6·62 KN. More recent data by Brinkmann *et al.* (1989) show an average maximum strength of 9·15 KN for L4/L5 segments of males under 40 years. of age. Typical distributions of compressive force of lumbar vertebral segments for both males and females under 'typical conditions of MMH activities' are badly needed. This includes cyclical loading of the spine to determine this effect on the compressive force limits. This will provide a better basis for the design of MMH tasks and will enhance the performance of biomechanical models.

3.1.1. *Biomechanical models:* Models are representation of the real system. By comparing a model's behaviour with the behaviour of the real system, it is possible to obtain an insight into the function and interactions of the system's components to achieve the desired goals. Biomechanical models represent the musculoskeletal system, and certain assumptions and simplifications are made to make the system less complex and easier to manage. Such models are used to determine the stresses imposed on the various components of the musculoskeletal system.

The several models that have appeared in the literature can be divided into two- and three-dimensional static and dynamic models. These models have been developed to determine stresses from manual handling activities. Some of the static models include Chaffin (1969), Martin and Chaffin (1972), Garg and Chaffin (1975), and Anderson *et al.* (1985). Dynamic models include those developed by Troup (1977), Ayoub and El-Bassoussi (1978), Garg *et al.* (1982), Leskinen *et al.* (1983a), Bejjani *et al.* (1984), Frievalds *et al.* (1984), Grieve (1984), McGill and Norman (1985), and Leskinen *et al.* (1983b). Most of these models use a single muscle equivalent to account for stresses, namely compressive and shear forces acting on the spine. Biomechanical models which involve many muscles are of limited practical value because they are mechanically indeterminate. Furthermore, the precise relation between the mechanical and electrical output of a muscle is uncertain (Ortengren and Andersson 1977). Hence, single muscle models appear to be satisfactory, for now, in analyzing two-handed symmetrical sagittal plane activities.

More contemporary models of the spine during simulated activities include those developed by Schultz and Andersson (1981), Gracovetsky *et al.* (1981), Schultz *et al.* (1982), Jager (1987), McGill and Norman (1986), Bean *et al,* (1988), and Chen and Ayoub (1988). These models are three-dimensional (3D) biomechanical models of the lumbar back based on several muscle groups to more accurately reflect the muscle activities and compression and shear loads on the spine. More unknown internal forces and fewer equations of equilibrium make 3D models of the trunk statically indeterminate. Therefore additional assumptions must be made to solve for the muscle tensions in these models. Some of these assumptions are yet to be validated.

The most obvious criticism of static models is that lifting is dynamic activity, therefore static models tend to underestimate forces and moments because the internal loads imposed by dynamic actions are ignored (Garg *et al.* 1982, Leskinen *et al.* 1983b, McGill and Norman 1985, and Kim 1990). Based on this literature it is

clear that inclusion of dynamic factors in biomechanical models is mandatory to estimate more accurately the moments and the forces on the various body joints including the lumbar spine. The inclusion of the effects of soft tissue and expanding these models to 3D would be more advantageous.

3.2. Physiological design approach

The physiological approach is concerned with the physiological stress on the body. In repetitive manual handling, large muscle groups (the extensors of the legs and back) perform dynamic contractions. During this type of work a workers's endurance is primarily limited by the capacity of oxygen transportation and utilization systems and not by his or her muscular strength (Astrand and Rodahl 1977, Chaffin, 1972).

As with the biomechanical approach, the goal of the physiological approach is to develop limits using metabolic and cardiovascular criteria and then determine lifting capacity based on the chosen criterion limit. Oxygen consumption or metabolic energy expenditure has been adopted as the criterion for repetitive lifting where the load is presumed to be within the physical strength of the individual. Bink (1964) concluded that a safe criterion for physiological work capacity for 8 h should be 33% of the maximum oxygen uptake.

Although basic laboratory evidence obtained from work on treadmills, bicycles, and hand cranks has fundamental importance, its application to manual materials handling activities must be approached with caution. Petrofsky and Lind (1978a) concluded that lifting a weight had a substantially higher oxgyen and ventilatory cost than similar levels of work on the bicycle ergometer. The reason for these differences appears to lie in the energy cost of moving parts of the body. If the current physiological criterion of 5 Kcal/min for 8 h work was based on the VO_2 max from the bicycle ergometer, the physiological criterion for lifting tasks might be 4 Kcal/min, according to Petrofsky and Lind's finding.

Therefore, if a physiological limiting criterion is selected, it should be based on the VO_2 max attainable for the particular lifting task under investigation, rather than for standard tasks such as bicycling or treadmill walking. The recent studies by Khalil et al. (1985), Fernandez (1986), and Kim (1990) confirm this contention.

3.2.1. Physiological models: As might be suspected, few researchers have tried to develop prediction models for energy cost of manual materials handling tasks. Frederick (1959) developed a simple linear model to estimate VO_2 for lifting activities. The energy consumed was determined based on lifting as a single performance. Garg (1976) used regression analysis to estimate metabolic energy expenditure rates for lifting and other activities. This model was further modified by Garg et al. (1978). Garg's model is based on the assumption that a job can be divided into simple tasks (activity elements), and that the average metabolic energy expenditure rate of the job can be predicted by adding the energy expenditures of the simple tasks.

Even though the models developed by Garg et al. (1978), Asfour (1980), and Karwowski and Ayoub (1984a) work very well with each of their respective data sets, Garg's model tends to overestimate and Asfour's model tends to underestimate the metabolic energy requirement for other data sets. The model by Karwowski and Ayoub appears to provide a more accurate estimation of oxygen consumption; however, its use is limited to analyses of lifting from floor to knuckle (FK) height.

Kim (1990) developed individual models to estimate VO_2 for lifting activities

from floor to knuckle (FK), floor to shoulder (FS), and knuckle to shoulder (KS) height. These models are functions of body weight, weight of load, and their interactions with frequency. To validate and compare some of these models, oxygen consumption rates and absolute percentage errors were calculated applying Kim's models and Garg's models using data sets from which the models were developed and three other data sets from other researchers, namely, Garg *et al.* (1978), Mital (1984), and Ostrom (1988). The same models were also used to estimate the loads to be lifted for given $\dot{V}O_2$ values. The absolute percentage error of these models generally ranged between 6% and 28% in predicting $\dot{V}O_2$.

Regression equations can be used to derive estimates of the independent or dependent variables. The direct estimate from the regression equation is more accurate than the inverse estimate from the alternative equation (Williams 1959). Therefore, estimation of load for a given oxygen consumption rate may be estimated from the oxygen consumption rate models. This must be used with caution, however, since this estimation may be less accurate than the direct estimation of the oxygen consumption rate. Absolute percentage error when using Garg's models and Kim's models to estimate the load for all three different data sets ranged from 22 to 340%.

In order to establish load limits based on physiological responses, more accurate load prediction models given a $\dot{V}O_2$ limit must be developed. These models must reflect additional variables such as container size, body twist, and task duration. When establishing limits for physiological criteria, one should use limits based on physical work capacity (PCW) for lifting rather than PWC for tasks other than lifting.

3.3. *Psychophysical design approach*

Psychophysics deals with the relationship between human sensations and their physical stimuli. Borg (1962) and Eisler (1962) found that the perception of both muscular effort and force obeys the psychophysical function where the sensation magnitude *S* grows as a power function of the stimulus *I*.

Snook (1978) stated that psychophysics has been applied to practical problems in many areas. With regard to manual materials handling, Legg and Myles (1981) stated that with good subject co-operation and firm experimental control, the psychophysical method can identify loads that subjects can lift repetitively for an 8 h workday without metabolic, cardiovascular, or subjective evidence of fatigue. The final weight selected by the subject is considered to be the maximum acceptable weight of lift (MAWL) for the given job conditions (frequency of lift, range of lift, container size, etc.). This approach has led to the development of capacity norms (Snook 1978, Ayoub *et al.* 1978a, Ayoub *et al.* 1983a).

3.3.1. *Psychophysically-based models:* Several lifting capacity prediction models using the psychophysical approach have been developed. These models include those by McConville and Hertzberg (1966) and Poulsen (1970). McDaniel (1972), Dryden (1973), and Knipfer (1974) developed regression models to predict the maximum acceptable weight of lift. These models employed various operator variables.

More recent models include those developed to predict MAWL as a function of operator and task variables. Based on two previous psychophysically determined lifting capacity data bases (Ayoub *et al.* 1978a, Snook, 1978), lifting capacity prediction models for both males and females were developed. These models can accommodate (1) a wide range of frequencies (0·1 to 12 lifts/min); (2) six ranges of lift; (3) various container sizes (12 to 30 inches in sagittal plane); and (4) both

individuals and different percentiles of a population. These models also allow for adjustment of lifting capacity based on presence or absence of handles and whether or not a twist of the body occurs during lifting activity. These models were also used to develop the job severity index (JSI) and its relationship to back injuries (Liles *et al.* 1984). Garg *et al.* (1980) conducted a psychophysical study to develop lifting capacity models by using a single strength (static or dynamic) variable. There are objections to lifting capacity models based on static strength tests because lifting is dynamic in nature (Kamon *et al.* 1982, Aghazadeh 1983). Consequently, dynamic strength should play a more important role in lifting than static strength. In recent years, psychophysical lifting capacity models based on dynamic strength tests have been developed by several researchers (Pytel and Kamon 1981, Kamon *et al.* 1982, Aghazadeh 1983, Jiang 1984). Although the psychophysical approach has been used by many investigators, Asfour (1980) and Karwowski (1982), in reviewing past psychophysical lifting studies, noted substantial discrepancies in the MAWLs reported in several studies. In addition Karwowski and Yates (1986) evaluated the psychophysical model for setting standards for the lifting range from floor to 76 cm above the floor, using seven female college students. They concluded that the psychophysical method in its present form may not be adequate for use in establishing lifting limits for frequencies greater than 6 lifts/min. More studies are needed to verify this conclusion.

4. Discussion

It has been noted by many authors and researchers (Brown 1971, Jones 1972, Snook and Ciriello 1972) that the subjective, best protective action in manual materials handling is to know one's limits and operate within them. It is generally believed that under a given set of conditions, persons should not lift more weight than they would be willing to accept based on their own point of view. On the other hand, the lifting capacity of an individual is limited by the metabolic energy expenditure rate and to a greater extent by the capability to resist and safely overcome stress, specifically on the low back.

There is, however, considerable disagreement among the three design approaches. Garg and Herrin (1979) have pointed out that there exists a trade-off between biomechanical stress criteria and physiological metabolic energy criteria. Biomechanical stress criteria, as we know it now, tend to minimize the load by using smaller, more frequent lifts, while physiological metabolic energy criteria tend to permit larger weights at less frequent intervals.

For infrequent lifting, the maximum acceptable weights of the load based on biomechanical stress criteria are generally higher than those based on the psychophysical fatigue criteria. For repetitive lifting the maximum acceptable weights based on psychophysical fatigue criteria are lower at low lifting frequencies and higher at high lifting frequencies than these based on physiological fatigue criteria (see figure 3) (Karwowski 1982, Kim 1990, Fernandez 1986).

The biomechanical approach assumes very infrequent lifting; therefore, the effects of fatigue have been ignored. Consequently, if the mechanical stresses applied to the musculoskeletal system are considered for frequent lifting the biomechanical approach is considered inadequate.

Static models assume no movement and therefore, the dynamic component of stress is assumed to be negligible. Such an assumption is erroneous and has resulted in gross errors in estimating stresses on the spine. Dynamic models are more

representative of the lifting motions and are thus preferred to static models. Obviously dynamic models require information about the kinematics of the lifting movement and are more difficult to develop and use. The current models assume that the effects of the passive tissue are negligible; these effects must be included in new models.

The physiological approach can be applied more reliably when the lifting task is performed repetitively (Khalil *et al.* 1985). For some limited task conditions, metabolic energy requirements can be measured or estimated from the models developed (Kim 1990, Garg 1976, Asfour 1980, Ayoub *et al.* 1980a). At this time, however, models do not provide accurate estimates of safe loads. Errors in estimation range as high as 212%.

One of the problems encountered in using the physiological approach is the limit of the energy expenditure to be chosen in arriving at the safe limit to lift. Should this be the 5 Kcal/min value? Or should one consider the fact that lifting PWC is less than the bicycle PWC (e.g., 2·6 l/min for the lifting activity with frequency of 7 lifts/min for the lifting range from floor to knuckle height as opposed to 3·5 l/min for the bicycling activity (Khalil *et al.* 1985))? Additional examples can be found in Petrofsky and Lind (1978a,b), Fernandez and Stubbs (1987), and Kim (1990). Or should one consider one third of the lifting PWC, especially since it is known that lifting PWC is a function of frequency of lift and is lower than the physical work capacity for bicycling?

The psychophysical method has been used for both frequent and infrequent lifting, including frequencies from as low as 1 lift every 8 h to as high as 18 lifts/min (Snook and Irvine 1968, Snook *et al.* 1970, Ayoub *et al.* 1978b, Ayoub *et al.* 1978a, Ayoub *et al.* 1980b). The technique assumes that the body integrates the stresses acting on it to arrive at the MAWL.

The assumption of psychophysical stress as an integration of physiological and biomechanical stresses has been studied by several researchers (Ayoub *et al.* 1980a, Jiang 1981). Karwowski (1982 and 1983) and Hafez *et al.* (1982) using fuzzy set theory concluded that the maximum acceptable weight of lift based on a psychophysical criterion appears to be the result of integrating the biomechanical and physiological stresses imposed by the lifting task. More investigations are needed to accurately estimate the combined stresses imposed on the body during MMH activities.

Psychophysics permits the realistic simulation of industrial work. For example, lifting can be a dynamic task through a given vertical distance, and not just an isometric pull. Also task frequency can be varied from very fast rates to very slow rates. Psychophysics also can be used effectively to study intermittent tasks that are commonly found in industry. Ciriello *et al.* (1990), in fact, reported that psychophysics is best used in studying these types of tasks.

It is clear from the literature that each of the three design approaches has its distinct advantages and disadvantages. It is also clear from figure 3, that differences in weight recommendations are found using these different approaches. In establishing safe lifting limits, one possibility is to consider the approach which gives the lowest weight among all three. Therefore, depending on the frequency of lift, one design criterion may be used to arrive at a weight limit, and another criterion may be used at other ranges or frequencies. This approach has been proposed by Kim (1990) in which he developed a comprehensive model to determine the lifting limits using all three design approaches simultaneously. Such an approach differs from the
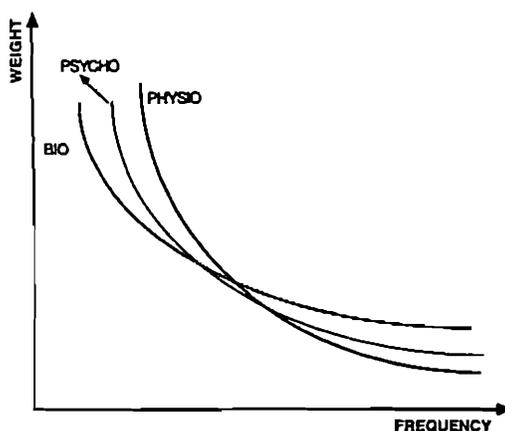
Figure 3. Comparison of biomechanical, physiological, and psychophysical fatigue criteria (Kim 1990).

approach used by NIOSH (1981) in which a limit under 'ideal conditions' is selected based on static strength values and corrected for vertical starting point, horizontal distance of the load, vertical lift distance, and frequency of lift. The approach proposed by Kim is to develop models to estimate the load limits for given compressive forces on the spine for a given $\dot{V}O_2$ and psychophysically-based models to estimate MAWL while lifting under specified task conditions. This approach leads to the development of a comprehensive model which determines the load limits given the compressive force limit, the energy expenditure limit, and the load limits based on perceived exertion. Such a model is depicted in Figures 4, 5, and 6 for the lifting ranges of floor to knuckle (FK), floor to shoulder (FS), and knuckle to shoulder (KS) heights, using a container size of $46 \times 30.5 \times 30.5$ cm with handles. In the biomechanics section of this model the moment arm for the erector spinae muscle has been increased from 5·0 cm to 7·5 cm (McGill *et al.* 1988). Therefore the estimates of the compressive forces were reduced from those reported by Kim (1990). Figure 4 presents the load limits based on the biomechanical approach, the physiological approach, and the psychophysical approach versus frequency of lift for lifting from floor to knuckle (FK). If one adopts the NIOSH limits of 3·43 KN compressive force for the AL, 6·37 KN compressive force for the MPL, 700 ML of O_2/min for the AL, and 1000 ML of O_2/min for the MPL, it is possible to use these limit weights for the various frequencies of lift without violating the biomechanical, physiological, and psychophysical criteria limits.

Figure 4 shows that using the AL 3·43 KN compressive force, the biomechanical approach is limiting until 5 lifts/min, after which the physiological approach becomes limiting. For the MPL 6·37 KN compressive force, the biomechanical approach is limiting until approximately 2 lifts/min; the psychophysical approach is then limiting until a frequency of approximately 5.5 lifts/min, after which the physiological approach becomes limiting.

Figure 5 shows that using the AL 3·43 KN compressive force, the biomechanical approach becomes limiting at 3 lifts/min, after which the physiological approach becomes limiting. For the MPL 6·37 KN compressive force, the biomechanical approach permits higher loads than the psychophysical approach. Therefore the
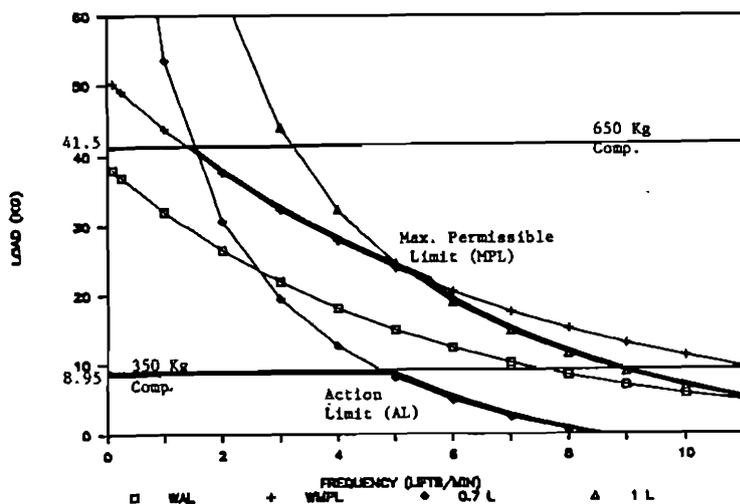
Floor—to—Knuckle Height Lifting

Figure 4. Comprehensive model for maximum weight limit for FK lifting.

Key:
WAL = weight limit (Kg) from the psychophysical model for AL criterion (99% male population);
WMPL = weight limit (Kg) from the psychophysical model for MPL criterion (25% male population);
700   = weight limit (Kg) from the physiological model for AL criterion (700 ml–O₂/min);
1000 = weight limit (Kg) from the physiological model for MPL criterion (1000 ml–O₂/min);
650   = weight limit (Kg) from the biomechanical model for MPL criterion (650 Kg comp. force).

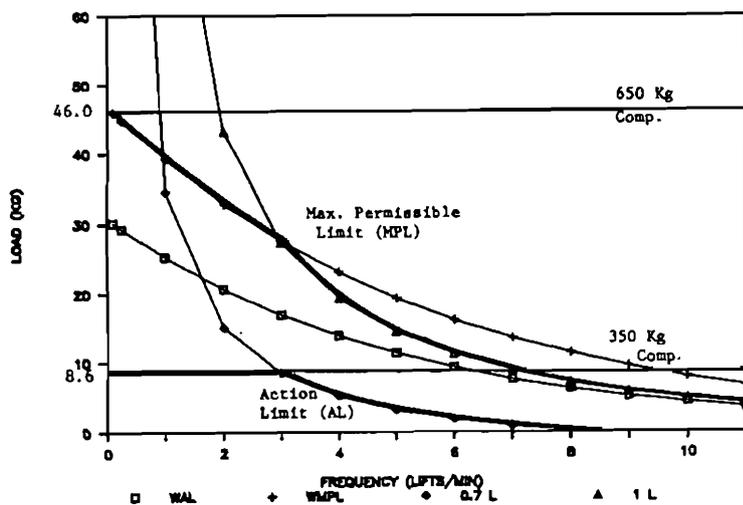## Floor—to—Shoulder Height Lifting

Figure 5. Comprehensive model for maximum weight limit for FS lifting.

Key:
WAL = weight limit (Kg) from the psychophysical model for AL criterion (99% male population);
WMPL = weight limit (Kg) from the psychophysical model for MPL criterion (25% male population);
700   = weight limit (Kg) from the physiological model for AL criterion (700 ml–O₂/min);
1000 = weight limit (Kg) from the physiological model for MPL criterion (1000 ml–O₂/min);
650   = weight limit (Kg) from the biomechanical model for MPL criterion (650 Kg comp. force).

psychophysical approach is limiting until 3 lifts/ min, after which the physiological approach becomes limiting.

Figure 6 for KS lifting presents similar information. At the AL the biomechanical approach is limiting until 3 lifts/min, after which the psychophysical approach becomes limiting. For the MPL 6·37 KN compressive force, the biomechanical approach permits higher weight than the psychophysical approach. Therefore the psychophysical approach becomes limiting at all frequencies because the physiological approach also permits heavier loads.
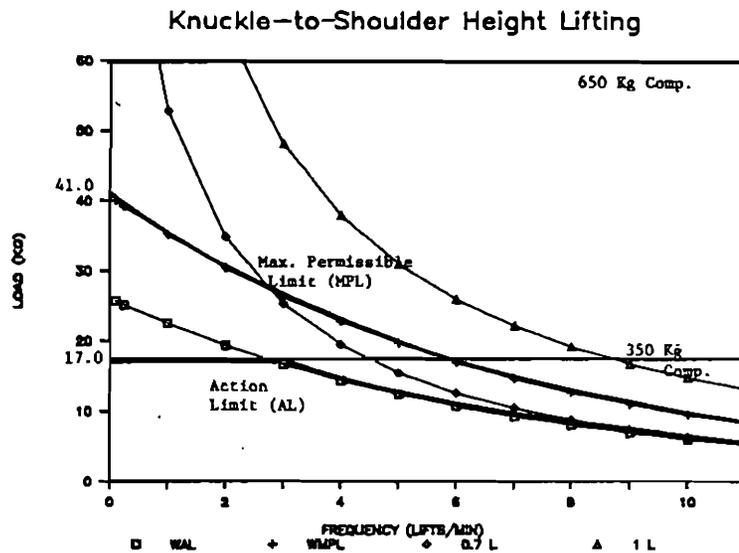
Knuckle—to—Shoulder Height Lifting

Figure 6.   Comprehensive model for maximum weight limit for KS lifting.

Key:
WAL   —weight limit (Kg) from the psychophysical model for AL criterion (99% male population);
WMPL —weight limit (Kg) from the psychophysical model for MPL criterion (25% male population);
700   —weight limit (Kg) from the physiological model for AL criterion (700 ml-O$_2$/min);
1000   —weight limit (Kg) from the physiological model for MPL criterion (1000 ml-O$_2$/min);
650   —weight limit (Kg) from the biomechanical model for MPL criterion (650 Kg comp. force).

More information about the comprehensive model and its components can be found in Kim (1990). To develop such comprehensive models, it is necessary to rely on supportive biomechanical, physiological, and psychophysical models. Using such supportive models which can estimate various percentile load limits, it is possible to use the comprehensive model not only for establishing safe limits, but also for making task design recommendations. It is therefore essential that these supportive models be accurate in predicting load limits and provide this information using a wide range of task variables.

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