Models in Manual Materials Handling

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INTRODUCTION

The ergonomics approach to manual materials handling (MMH) tasks defines a Man-Task-Environment System. A generally accepted means of minimizing MMH related injuries is to design MMH tasks so that the demands of the tasks are less than the capacities of the individuals performing these tasks. Task design is dependent, in part, on the availability of comparable data for task demands and worker capacities. The generation of the appropriate data is dependent, in part, on being able to identify the pertinent capacity parameters of manual materials handling activities.

In the past, a substantial effort has been directed at determining 'safe' lifting capacities for individuals and groups of individuals. The assumption used for these studies was that there is a relationship between an individual's capacity and his or her injury potential. In other words, a person with a small capacity with respect to a given task demand is more likely to be injured than another person with larger capacities. For the measurement of a safe and permissible lifting capacity three approaches are commonly used. The first approach is the biomechanical approach, the second approach is the physiological approach, and the third is the psychophysical approach. These three approaches and the models developed using the selected criterion under each approach are discussed below.

THE BIOMECHANICAL APPROACH

Using the biomechanical approach, researchers attempt to model directly the mechanical stresses placed upon the internal structures of the body during lifting. The goal of this approach is to accurately estimate how work activities stress the bones, muscles and connective tissues of the body and to predict when these stresses will lead to damage of these structures. This approach is very popular in ergonomics because it closely corresponds with most expert views of the aetiology of injury during manual materials handling (NIOSH, 1981).

Biomechanical models typically model the human body as a series of mechanical links and joints corresponding to the human skeleton. Both external forces, needed to perform the work activity, and internal forces, as a result of muscle contraction, are modeled to estimate the mechanical stresses. Most models focus on estimating only a few mechanical stress parameters related to the injury of interest in the analysis. For manual materials handling the parameter most often selected is the compressive force on the low back, usually the L5/S1 spine segment.

The criterion selected

The criterion selected in most biomechanical analyses of manual materials handling has been greatly influenced by the National Institute for Occupational Safety and Health's (NIOSH) guidelines for Manual Lifting (NIOSH, 1981, 1994). In developing a biomechanical criterion, NIOSH arrived at the following three conclusions based upon a review of the literature (NIOSH, 1994):

(1) The joint between L5 (fifth lumbar) and S1 (first sacral) is the joint of greatest lumbar stress during lifting.

(2) Compressive force (at this joint) is the critical stress vector.

(3) The compressive force criterion that defines increased risk is 3.4 kN.

Support for these assumptions can be found in both NIOSH documents (NIOSH, 1981, 1994) and in epidemiological studies by Herrin *et al.* (1986), Bringham and Garg (1983), Anderson (1983), and Chaffin and Park (1973). However recent work by Leamon (1994) suggests that more research is needed in this area.

Several other criteria have been used to a lesser extent in biomechanical modeling, including the external hip moment, the external moment at L5/S1 joint, anterior-posterior (A-P) shear force, and lateral shear force. In addition, Man-as *et al.* (1993) have recently proposed using kinematic parameters of the torso as criterion to predict injury (Marras *et al.*, 1993, 1995). Because most models attempt to predict compressive force, A-P shear force, and lateral shear force at the lower back (either L5/S1 or L3/L4), the rest of this section will focus on these criteria.

Estimating the external load moment

All biomechanical models employed to evaluate lifting begin by knowing the external load placed on the body by the task under study. The procedure used for this calculation in different models is essentially the same, with slight differences in the kinematic representations of the body and the anthropometric and body segment data that are used in the calculation. The skeleton of the body is modeled as a series of rigid links or levers connected at frictionless pin joints. With several other assumptions, engineering mechanics is used to calculate the moment created by the force acting at the hands at each joint, beginning with joints closest to the hands and ending at the joint of interest (usually the L5/S1 or L4/L5 intervertebral joints). Implicit in the construction of these models are simplifying assumptions regarding the number and geometric complexity of the joints and bones of the human body.

Biomechanical models are either two-dimensional or three-dimensional and either static or dynamic. For static models, the calculations require information on the orientation of the links in the model (subject's posture), the length of each segment, the mass of each segment, and the location of the center-of-mass of each segment. Dynamic models require this same information plus the angular joint accelerations, linear acceleration of each segment at the center-of-mass, and the moment-of-inertia of each link through the center of mass. A general equation to calculate the static moment at successive joints in a linkage is:

$$\underline{M}_{joint} = \underline{M}_{joint-1} + (\underline{L}_{link} \times \underline{F}_{joint-1}) + (\underline{CM}_{link} \times m_{link}\,\underline{G}) \tag{1}$$

where:

$\underline{M}_{joint}$ is the reactive load moment vector for the joint of interest,
$\underline{M}_{joint-1}$ is the reactive load moment vector for the joint previous to the joint of interest in the linkage,
$\underline{L}_{link}$ is the vector from the position of the joint of interest to the previous joint,
$\underline{F}_{joint-1}$ is the reactive force for the joint previous to the joint of interest,
$\underline{CM}_{link}$ is the vector from the position of the joint of interest to the center-of-mass position for that link,
m_{link} is the mass of the link, and
$\underline{G}$ is the vector representing acceleration due to gravity.

For dynamic models, an equivalent equation is:

$$\underline{M}_{joint} = \underline{M}_{joint-1} + (\underline{L}_{link} \times \underline{F}_{joint-1}) + (\underline{CM}_{link} \times m_{link}\,\underline{G}) + (\underline{CM}_{link} \times m_{link}\,\underline{A}_{link}) + (\ddot{\underline{\theta}}_{joint} \times \underline{I}_{link}) \tag{2}$$

where:

$\underline{M}_{joint}$ is the reactive load moment vector for the joint of interest,
$\underline{M}_{joint-1}$ is the reactive load moment vector for the joint previous to the joint of interest in the linkage,
$\underline{L}_{link}$ is the vector from the position of the joint of interest to the previous joint,
$\underline{F}_{joint-1}$ is the reactive force for the joint previous to the joint of interest,
$\underline{CM}_{link}$ is the vector from the position of the joint of interest to the center-of-mass position for that link,
m_{link} is the mass of the link,
$\underline{G}$ is the vector representing acceleration due to gravity,
$\underline{A}_{link}$ is the instantaneous linear acceleration vector of the link center-of-mass,
$\ddot{\underline{\theta}}_{joint}$ is the angular acceleration of the link about the joint of interest, and
$\underline{I}_{link}$ is the moment-of-inertia of the link through the center-of-mass.

Anthropometric data needed for these equations can be found in a number of sources including Dempster (1955), Clauser *et al.* (1969) and NASA (1978). Additional details on how to calculate external load moments can be found in Chaffin and Andersson (1991), Winter (1990), Ozkaya and Nordin (1991) and Williams and Lissner (1977).

Estimating internal muscle forces

The forces acting on the intervertebral discs are a combination of the external forces at the joints and the internal forces created by muscles and connective tissues. For two-dimensional models, muscle forces are usually estimated by assuming that the erector spinae muscle acts to generate force if the external load moment at the torso is acting to increase torso flexion (i.e., lifting activities) and the rectus abdominus muscle is active if the external load moment at the torso is acting to decrease torso flexion (i.e. pushing down). For static models, the muscle forces can be derived using the conditions of static equilibrium. For dynamic activities, Newton's second law can be used. The most popular two-dimensional static biomechanical model currently in use is the University of Michigan's *2D Static Strength Prediction Program.* In addition to using the erector spinae muscles and the rectus abdominus muscles, this model also adds internal forces due to the interabdominal pressure (IAP) created by the muscles of the torso during lifting activities. The use of interabdominal pressure in biomechanical models has been questioned by several researchers (Mairiaux and Malchaire, 1988; McGill and Norman, 1986) and is not generally included in most three-dimensional models. In addition to disc compressive forces, the University of Michigan's *2D Static Strength Prediction Program* also predicts muscle strength at each joint included in the model.

Estimating internal muscle forces has proven to be difficult for three-dimensional models due to the complexity of the human torso. Because the number of muscles in the torso region is generally greater than the number of force and moment equations, the problem is indeterminate. Optimization procedures were first employed to solve for the static three-dimensional muscle forces in the torso by Schultz *et al.* (1983). This model was later refined into the minimum-intensity-compression (MIC) model (Bean *et al.*, 1988). The model employs a two-step linear programming approach to estimating the internal muscle forces. The first step in the procedure:

$$\text{Minimize } I \tag{3}$$

subject to:

$$\sum_{i=1}^{m} \left\| f_i \right\| \left(\underline{r}_i \times \underline{\tau}_i \right) + \underline{M}_{joint},$$

$$\frac{f_i}{A_i} \leq I,$$

$$f_i \geq 0,$$

where:

f_i is the tension in each muscle,
$\underline{r}_i$ is the moment arm vector,
$\underline{\tau}_i$ is the muscle line-of-action vector,
$\underline{M}_{joint}$ is the reactive load moment for the joint of interest,

finds the minimum—maximum muscle intensity for the muscles being considered in the model. Intensity is defined as the force exerted by the muscle divided by the cross-sectional area of the muscle. The second step in the procedure:

$$\text{Minimize } \left\| f_i \right\| \underline{\tau}_i^{z} \tag{4}$$

subject to:

$$\sum_{i=1}^{m} \|f_i\| \left(\underline{r}_i \times \tau_i\right) + \underline{M}_{joint},$$

$$\frac{f_i}{A_i} \leq I^*,$$

$$f_i \geq 0,$$

where:

f_i is the tension in each muscle,
$\underline{r}_i$ is the moment arm vector,
$\underline{\tau}_i$ is the muscle line-of-action vector,
$\underline{M}_{joint}$ is the reactive load moment for the joint of interest,
I^* is the minimum intensity value from the first step in the procedure,

selects muscle forces which satisfy the minimum intensity criteria generated in the first step and also minimizes the compressive force on the intervertebral disc. The second step is only needed if multiple optima are found in the first step which seldom occurs in practical application of the model. This model is included in the University of Michigan's *3D Static Strength Prediction Program.* The main output screens of this computer program for a typical lifting task are shown in Figure 1.

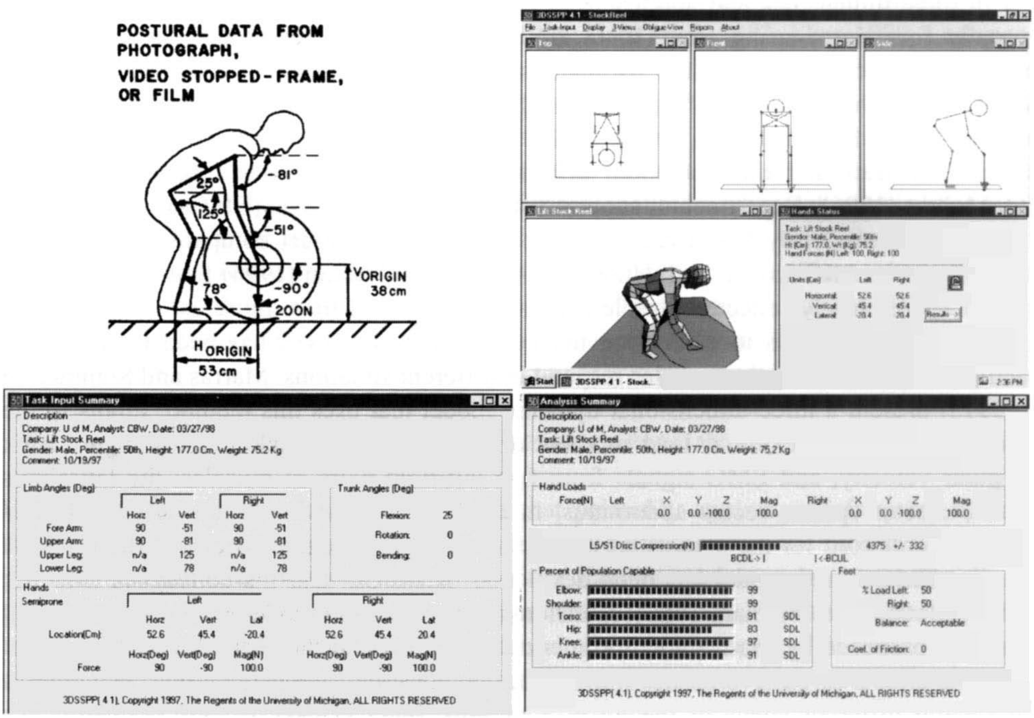

Figure 1. Work task and main output screens for the University of Michigan's *3D Static Strength Prediction Program* (reprinted with permission from the University of Michigan, 1998).

A second optimization model often used to estimate static muscle force in the torso is the sum of cubed intensities (SCI) model first proposed for use in modeling the extremities by Crowminshield and Brand (1981). While similar to the MIC model, this algorithm employs non-linear programming which makes the solution procedure, in general, more difficult. The SCI optimization model is formulated as:

$$\text{Minimize} \quad \sum_{i=1}^{m} \left(\frac{f_i}{A_i} \right)^3 \tag{5}$$

subject to:

$$\sum_{i=1}^{m} \|f_i\| \left(\underline{r}_i \times \tau_i \right) + \underline{M}_{joint},$$

$$f_i \geq 0,$$

where:

f_i is the tension in each muscle,
$\underline{r}_i$ is the moment arm vector,
$\underline{\tau}_i$ is the muscle line-of-action vector,
$\underline{M}_{joint}$ is the reactive load moment for the joint of interest,

Both the MIC and the SCI optimization procedures do not restrict the number of muscle forces predicted, but they require information on the cross-sectional area of the muscles, the muscle line of action, and the muscle moment arm vector. This information must be in three dimensions and applicable to the joint of interest in the model. Models are usually formulated using from 10 to 22 different muscles about the torso. Relevant anthropometric values for these parameters can be found a variety of sources (Chaffin *et al.*, 1990; Dumas *et al.*, 1988; Han *et al.*, 1992; Macintosh and Bogduk, 1986; McGill *et al.*, 1988; Schultz *et al.*, 1983; Tracy *et al.*, 1989). A review of different torso anthropometries and their potential effects on optimization models can be found in McMulkin (1996). Experimental support using electromyographs (EMGs) was provided for the MIC model by Ladin *et al.* (1989); however, in a direct comparison of the SCI model and the MIC model, both Hughes (1991) and McMulkin (1996) found that the SCI model more closely reflected muscle activation patterns of torso muscles.

A second approach to estimating the internal muscle forces has been to use EMG activity to predict how the muscles respond in different situations. Marras and Sommerich (1991a) present a three-dimensional dynamic model that uses this method. Inputs to the model include the external load moment at the trunk, the trunk flexion angle, trunk angular velocity, and EMG signals from five left/right pairs of muscles: the latissimus dorsi, erector spinae, rectus abdominus, internal oblique, and external oblique. EMGs must be collected for the activity of interest and for maximum exertions of the trunk. A similar EMG based model has been developed by McGill and his colleagues (McGill, 1992; McGill and Norman, 1986). A difference between the model proposed by McGill and that proposed by Marras and Sommerich (1991a) is that the McGill model incorporates the effects of passive tissues into the calculations and it considers muscle activities at several different levels of the torso. Kee and Chung (1996) recently compared the predictions of the Marras and Sommerich (1991a) biomechanical model to those of the MIC model. The MIC model was applied to a dynamic lifting situation by sequentially applying the model at consecutive time intervals throughout the lift. The results of this comparison demonstrated substantial differences between the predictions of the two models, especially for asymmetric tasks.

A third class of biomechanical model has recently been proposed which incorporates both optimization and EMG components to estimate internal muscle forces. Nussbaum and Chaffin (1996) recently proposed an artificial neural network model that uses EMG signals as a learning tool. The model takes as input the external load moment at the torso and produces as output muscle activities for four left/right pairs of muscles: the latissimus dorsi, erector spinae, rectus abdominus, and external oblique. A quantitative evaluation of the model performed by Nussbaum and Chaffin (1996) indicates remarkable agreement with measured EMG signals. Cholewicki and McGill (1996) have also developed a model that employs both EMG and optimization techniques. This model estimates muscle forces using EMG signals as inputs and then adjusts to force using an optimization routine.

The effect of task variables on model predictions

Biomechanical models have been used to evaluate the effects of many different task variables on workers performing manual materials handling tasks. Most biomechanical models are very sensitive to the magnitude of the load and position of the load in relation to the position of the torso. Increasing the load, moving the load away from the body, and moving the load down from waist level to the floor substantially increases the L5/S1 compressive force as shown in Figure 2. These estimates were produced using a two-dimensional static model similar to the University of Michigan's *2D Static Strength Prediction Program.*

Static biomechanical models have been reported to under-estimate the forces associated with dynamic activities (Freivalds *et al.*, 1984; Garg *et al.*, 1982; Kim, 1990; Leskinen *et al.*, 1983; Man-as and Sommerich, 1991b; McGill and Norman, 1986). The peak compressive force during a dynamic lift activity usually occurs as the load is being accelerated during the motion. For activities with relatively large accelerations, the static estimate of the compressive force at this point is 30-40 per cent lower than the dynamic estimate (Granata and Marras, 1996). Three-dimensional biomechanical models have also shown that asymmetric lift activities result in higher compressive force than symmetric lifts. This occurs for two handed lifts with a twisted body posture (Chen, 1988; Marras and Sommerich, 1991b; Mital and Kromodihardjo, 1986), one handed lifts (Davis *et al.*, 1997), and for team lifts with asymmetric body postures (Marras *et al.*, 1997).

PHYSIOLOGICAL DESIGN APPROACH

Unlike the biomechanical design approach that primarily applies to infrequent lifting, the physiological approach is applicable to repetitive lifting where the load is within the physical strength of the worker. During repetitive handling tasks, a person's endurance is primarily limited by the capacity of the oxygen transport system. As muscles contract and relax, their increased metabolic energy demand requires an increase in the delivery of oxygen and nutrients to the tissues. If this demand for increased oxygen and nutrients cannot be met, the activity cannot be sustained for long.

When a person is engaged in physical work, such as MMH activities, several physiological responses are affected. These include metabolic energy cost, heart rate, blood pres-

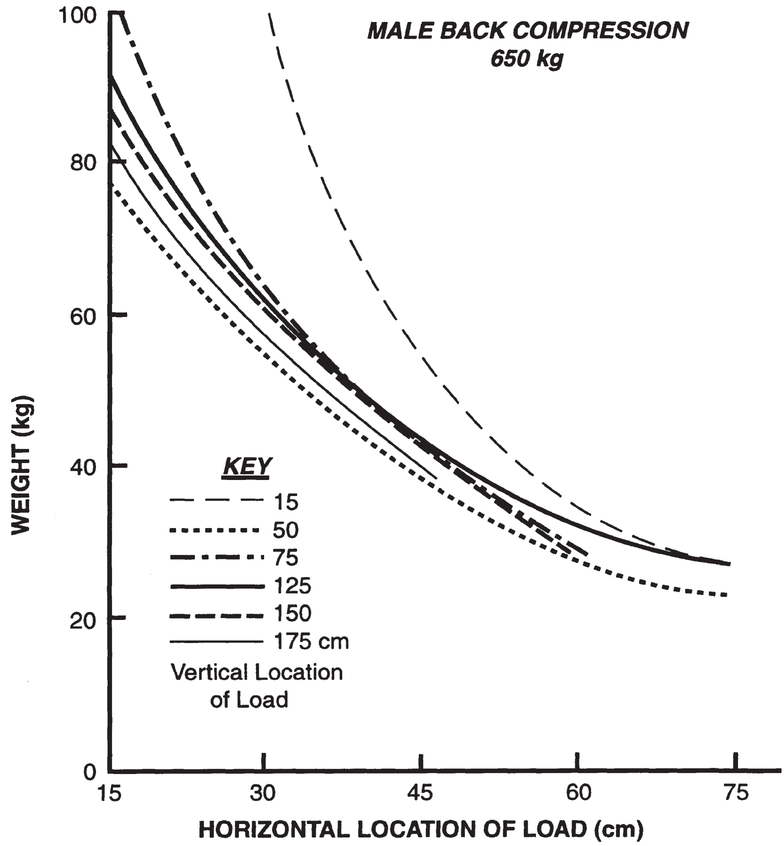

Figure 2. Relationship between the load weight, the horizontal distance away from the spine, and the vertical distance of the load from the floor for a constant 650 kg L5/S1 compressive force (from NIOSH, 1981).

sure, blood lactate, and ventilation volume. Of all these responses, metabolic energy expenditure has been the widely accepted physiological response to repetitive handling as it is directly proportional to the workload at steady-state conditions (Aquilano, 1968; Astrand and Rodahl, 1986; Ayoub *et al.*, 1981; Durnin and Passmore, 1967; Hamilton and Chase, 1969; Mital, 1984). For this reason, this discussion will exclusively focus on metabolic energy expenditure rate as the physiological approach design criterion.

Several work- and workplace-related factors affect metabolic energy expenditure rate. Table 1 summarizes these factors and their net effect on oxygen consumption. For a detailed discussion on the effect of these and personal factors on oxygen consumption the reader is referred to *Manual Materials Handling* by Ayoub and Mital (1989).

There is a need for models that can predict the physiological cost (e.g., oxygen consumption and heart rate) of individuals engaged in repetitive manual materials handling (MMH) tasks. Physiological cost models are used in industry to: determine whether or not the task is within the expected capability of the population; and determine the work/rest schedule for a given task (Asfour, 1980). The literature on physiological cost prediction models for MMH tasks grew in the 1980s. This section will review the existing energy and cardiac cost prediction models for several manual materials handling activities. This by no means is an exhaustive review.

Table 1. Net effect of work and workplace factors on metabolic energy.

Factor		
Frequency of handling (↑)	All	Increase
Task duration (↑)	All	Increase[a]/ decrease[b]
Object size (↑)	All	Increase
Couplings (good)	All	Decrease
Object shape (various)	All	Unknown
Object weight/force (↑)	All	Increase
Load stability/distribution	Lifting, carrying	Unknown
Vertical height (↑)	Lifting, lowering	Increase
Distance travelled (↑)	Pushing, pulling, carrying	Increase
Speed/grade (↑)	Pushing, pulling, carrying	Increase
Asymmetrical handling	Lifting	None

(From Mital et al., 1997).
↑ increase; [a] if the weight/force does not change; [b] if the weight/force decreases (e.g., when using the psychophysical methodology).

Energy and cardiac cost for lifting/lowering models

Several researchers have developed prediction models for the energy and cardiac cost responses of individuals engaged in repetitive manual materials handling tasks. Research in this area has been carried out by Aberg *et al.* (1968), Asfour (1980), Chaffin (1967), Frederick (1959), Garg (1976), Karwowski and Ayoub (1984a), Liou and Morrissey (1985), Mital (1983b, 1985), Mital *et al.* (1984) and Morrissey and Liou (1984a, 1984b, 1984c). A list of several energy cost and cardiac cost models is given in Tables 2 and 3. The cardiac cost models are summarized in Table 4.

Frederick (1959) developed a model to predict the consumption of energy for various weights in four different ranges. Chaffin's model (1967) was developed for static weight-holding activities in the sagittal plane. Aberg *et al.* (1968) developed a model based on the principle that mechanical work is related to a change of the positional energy of mass and frictional losses. Garg (1976) and Garg *et al.* (1978) used step-wise regression analysis to develop models for lifting, lowering, and carrying activities. Ayoub *et al.* (1980) provided a review of the energy cost models for manual lifting tasks developed by Aberg *et al.* (1968), Chaffin (1967), Frederick (1959) and Garg (1976).

Asfour (1980) developed and tested energy cost prediction models for manual lifting and lowering using stepwise regression models, and attempted to overcome some of the limitations cited by Ayoub *et al.* (1980) by studying the effect of task variables and their interactions on lifting and lowering tasks. The estimated energy expenditure for 512 tasks was based on frequency of lift or lower (3, 6, 9 times/min), load lifted or lower (6.8, 13.6, 20.4 kg), range of height (floor–76 cm, 76–127 cm, floor–127 cm), box width (38, 66 cm), box length (38, 66 cm), and angle of twist of the body (0, 90 degrees). The models developed were reported later by Asfour *et al.* (1985).

Karwowski and Ayoub (1984a) developed a model to estimate the oxygen consumption associated with the maximum weight (MAW) of lift, determined psychophysically, for frequencies of 0.1, 3, 9, and 12 lifts/min when lifting from floor to table height (76 cm). The inputs to the model are the frequency of lift, maximum acceptable load weight, body weight, and age. This model is presented in Table 2.

Table 2. Energy cost prediction models for lifting tasks.

Source	Dependent variable	Type of task	Model
Frederick (1959)	Total energy expenditure per hour	Lifting from floor to 20 in, 20 in to 40 in, 40 in to 60 in and 60 in to 80 in	TEE = (Number of lifts/ hour)*(lifting height in feet)* (weight of load in pounds) * (energy consumption in gm cal/foot pound)/1000
Garg et al. (1978)	Net metabolic rate (kcal/lift)	Stoop lift (h1 < h2 ≤ 0.81)	NMR = 0.00325 * W * (0.81 – h1) + (0.0141 * L + 0.0076 * G * L) * (h2 – h1)
Garg et al. (1978)	Net metabolic rate (kcal/lift)	Squat lift (h1 < h2 ≤ 0.81)	NMR = 0.00514 * W * (0.81 – h1) + (0.0219 * L + 0.0062 * G * L) * (h2 – h1)
Garg et al. (1978)	Net metabolic rate (kcal/lift)	Arm lift (0.81 < h1 ≤ h2)	NMR = 0.00352 * W * (0.81 – h1) + 0.0303 * L * (h2 – h1)
Asfour (1980)	Oxygen consumption (ml/min)	Lifting that starts at floor and lowering that ends at floor	V02 = 545.7538 – 106.4477 * TA + 10** – 6 * F * L**2 * (35002.65 – 35058 * L) + 17.47 * 10** – 6 * F * L * H * WID * LEN * ANG + 16435.22 * 10** – 6 * W * F**2
Asfour (1980)	Oxygen consumption (ml/min)	Lifting that starts at table height and lowering that ends at table height	V02 = 371.5055 – 51.9573 * TA + 10** – 6 * W * F**2 * (31856.54 – 2332.8 * F) + 12684.91 * 10** – 6 * F * L**2 + 12.31 * 10** – 6 * F * H * L * W * LEN * ANG
Mital (1983b) and Mital et al. (1984)	Change of oxygen consumption with time (%)	Lifting (males)	CV02 = 103.763 – 13.497 * T + 2.142 * T**2 – 0.117**3 + 0.00013 * EXP(T)
Mital (1983b) and Mital et al. (1984)	Change of oxygen consumption with time (%)	Lifting (females)	CV02 = 101.726 – 2.305 * T + 0.00003 * EXP(T)
Mital et al. (1984)	Oxygen consumption (l/min)	Lifting from floor to knuckle	V02 = 1.527 – 0.207 * G – 0.005 * Stature + 0.0013 * Back Strength – 0.0002 * Chest Width**2 + 0.203 * LOG (Shoulder Strength) – 0.408 * LOG (Back Strength) – 0.02 * Shift Duration + 0.161 * LOG(F) + 0.002 * F * Lifting Capability – 0.0007 * F * Box Size
Mital et al. (1984)	Oxygen consumption (l/min)	Lifting from knuckle to shoulder	V02 = 0.047 – 0.117 * G – 0.003 * Age + 0.0005 * Chest Depth**2

Table 2 (Continued).

Source	Dependent variable	Type of task	Model
			– 0.00001 * Composite Strength**2 – 0.00005* Back Strength ** 2 – 0.175*LOG(Arm Strength) – 0.0084 * Shift Duration + 0.004 * F * Lifting Capability + 0.00002 * Box Size * Lifting Capability
Mital et al. (1984)	Oxygen consumption (l/min)	Lifting from shoulder to reach	V02 = – 0.521 – 0.123 * G + 0.004 * W + 0.25 * LOG(Arm Strength) – 0.008 * Shift Duration + 0.004 * F * Lifting Capability + 0.0003 * Box Size * Lifting Capability
Mital et al. (1984) and Mital (1985)	Oxygen consumption (l/min)	Lifting for all heights	V02 = 0.86 – 0.168 * G + 0.00002 * W**2 – 0.00012 * Arm Strength**2 + 0.279 * LOG(Arm Strength) – 0.231 * LOG(Back Strength) – 0.013 * Shift Duration + 0.004 * F * Lifting Capability – 0.00012 * Box Size * Lifting Capability
Karwowski and Ayoub (1984a)	Oxygen consumption (l/min)	Lifting from floor to 76 cm above floor	V02 = 0.1659 + 0.004026 * F * Lifting Capability + 0.0026887 * Lifting Capability + 0.002873 * W – 0.005854 * Age + 0.032699 * F

(From Genaidy and Asfour, 1987; reprinted with permission.)

TEE – energy expenditure/hour
NMR – net metabolic rate for the activity performed
V02 – oxygen consumption (l/min for all studies, except Asfour in ml/min)
CV02 – change of oxygen consumption with time (%)
W – body weight (kg in Garg et al. and Mital et al.; pounds in Asfour)
L – amount of load handled (kg in Garg et al. and Mital et al.; pounds in Asfour)
G – gender (Garg, et al.: male = 1, female = 0; Mital et al.: male = 1, female = 2)
h1 – vertical height from floor (m); starting point for lift
h2 – vertical height from floor (m); end point for lift
TA – type of task (lifting = 1, lowering = 2)
F – frequency of handling (times/min)
H – height of lift or lower (inches)
WID – box width (inches)
LEN – box length (inches)
ANG – angle of twist (0° twist = 1; 90° twist = 2)
T – shift duration (minutes)

All anthropometric measurements in cm; isometric strengths in kg; lifting capability in kg; box size in inches; age in years; all models are valid for a duration of less than one hour, except those of Mital, which are valid up to 12 hours.

Table 3. Energy cost prediction models for lowering tasks.

Source	Dependent variable	Type of task	Model
Garg et al. (1978)	Net metabolic rate (kcal/lower)	Stoop lower (h1 < h2 ≤ 0.81)	NMR = 0.00268 * W * (0.81 – h1) + 0.00675 * L * (h2 – h1) + 0.0522 * G * (0.81 – h1)
Garg et al. (1978)	Net metabolic rate (kcal/lower)	Squat lower (h1 < h2 ≤ 0.81)	NMR = 0.00511 * W * (0.81 – h1) + 0.00701 * L * (h2 – h1)
Garg et al. (1978)	Net metabolic rate (kcal/lower)	Arm lower (0.81 < h1 < h2)	NMR = 0.00093 * W * (h2 – 0.81) + (0.0102 * L + 0.0037 * G * L) * (h2 – h1)
Asfour (1980)	Oxygen consumption (ml/min)	Lifting that starts at table height and lowering that ends at table height	See Table 2
Asfour (1980)	Oxygen consumption (ml/min)	Lifting that starts at floor level and lowering that ends at floor lever	See Table 2

(From Genaidy and Asfour, 1987; reprinted with permission.)

NMR – net metabolic rate for activity performed
W – body weight (kg)
L – amount of load lowered (kg)
G – gender (male = 1, female = 0)
h1 – vertical height from floor (m); end point for lower
h2 – vertical height from floor (m); starting point for lower
All models are valid for a duration of less than one hour.

Table 4. Cardiac cost prediction models for lifting tasks.

Source	Type of Task	Model
Mital (1983b) and Mital et al. (1984)	Lifting for males	CHR = 104.846 – 16.85 * Shift Duration + 3.215 * Shift Duration** 2 – 0.184 * Shift Duration** 3 + 0.0002 * EXP (Shift Duration)
Mital (1983b) and Mital et al. (1984)	Lifting for females	CHR = 100.36 – 16.85 * Shift Duration + 0.00004 EXP (Shift Duration)
Mital et al. (1984)	Lifting from floor to knuckle height	HR = – 112.342 + 14.677 * G – 0.713 * Iliac Crest Height – 1.793 * Chest Depth + 3.494 * Abdominal Depth + 12.078* RPI – 0.0045 * (Back Strength) ** 2 + 18.35 * LOG(Arm Strength) + 3.367 * Frequency – 0.772 * Shift Duration + 1.885 * Lifting Capability – 0.01 * Box Size * Lifting Capability – 0.48 * Age
Mital et al. (1984)	Lifting from knuckle to shoulder height	HR = 1225.276 + 17.693 * G + 1.656 * Abdominal Depth + 7.37 * RPI + 0.62 * Back Strength + 0.02 * (Knee Height)**2 + 0.0024 * (Composite Strength)**2 – 0.0095 * (Back Strength)**2 – 279.375 * LOG(Stature) + 37.582 * LOG(Forearm

Table 4 (Continued).

Source	Type of Task	Model
		Grip Distance) – 16.853 * LOG(Chest Width) – 0.986 * Shift Duration + 0.231 * Lifting Capability * Frequency + 0.01 * Box Size * Lifting Capability
Mital et at. (1984) Composite	Lifting from shoulder to reach height	HR = 39.176 + 17.015 * G – 0.56 * Iliac Crest Height + 0.613 * Arm Strength – 0.378 * Strength + 25.743 * LOG(Back Strength) + 0.003 * (Composite Strength)**2 – 0.009 * (Back Strength)**2 – 1.32 * Shift Duration + 6.43 * LOG (Frequency) + 0.067 * Frequency * Lifting Capability + 0.005 * Box Size * Lifting Capability
Mital et al. (1984) and Mital (1985)	Lifting for all heights	HR = 136.943 + 18.565 * G + 0.09 * (Abdominal Depth)**2 – 0.004 * (Back Strength)**2 – 47.227 * LOG(Body Weight) + 40.215 * LOG(Forearm Grip Distance) – 40.698 * LOG (Abdominal Depth) + 11.476 * LOG(Arm Strength) + 11.366 * LOG(Composite Strength) – 0.96 * Shift Duration + 0.246 * Frequency * Lifting Capability – 0.009 Box Size * Lifting Capability – 0.425 * EXP(H)

(From Genaidy and Asfour, 1987; reprinted with permission.

Anthropometric measurements in cm
Isometric strengths in kg
Frequency in lifts/minute
Lifting capability in kg
Box size in inches
Body weight in kg
H (height of lift): floor to knuckle = 1, knuckle to shoulder = 2, shoulder to reach = 3
G (gender): male = 1, female = 2
Shift duration in hours
RPI = Height/3 * ((Body Weight)**0.333)
Age in years
HR (heart rate) in beats/min
CHR (change in heart rate with time) in %
All models are valid for a duration of up to 12 hours.

Mital (1983a) and Mital *et al.* (1984) developed oxygen consumption and heart-rate prediction models as a function of working time. The maximum weight of lift (MAWL) for these models was determined psychophysically. The oxygen consumption and heart rate associated with the maximum acceptable weight were recorded every two hours for 12 hours. The models are listed in Table 2.

In other studies, Mital (1985) and Mital *et al.* (1984) developed metabolic and cardiac prediction models for lifting tasks. The models were based on task variables as well as anthropometric and strength measurements using experienced subjects. Four lifting frequencies (1, 4, 8, 12 times/min), three height levels (floor to knuckle, knuckle to shoulder, shoulder to reach), and three box sizes (30.5, 45.7, 70.0 cm long in the sagittal plane) were used as the levels of the independent variables. The models developed showed low multiple R-square values (between 0.59 and 0.60). The models are listed in Table 2.

Energy and cardiac cost models for carrying

Morrissey and Liou (1984a, 1984b) conducted experiments to develop models to predict the energy cost of two handed carrying of loads in front of the body. Twenty-seven different carrying tasks were used on a level treadmill. The different variables involved in the carrying tasks were treadmill speed (0.89, 1.12, 1.34, 1.56, 1.79 m/sec), container weight (0, 4.5, 11.3, 18.1, 22.7 kg), and container width in the sagittal plane (15.2, 22.8, 30.5 cm). Also included as variables were stature (as percentage of normal stature) and walking speeds. Regression models were developed to predict the steady state heart and metabolic rates; the regression models developed for oxygen consumption and heart rate are given in Tables 5 and 6.

Morrissey and Liou (1984c) also examined the physiological costs of carrying loads in erect and non-erect postures. Four trained male subjects carried loads on a level treadmill with a range of walking postures, container widths, container weights and walking speeds. The steady state oxygen uptake and heart rate required for task performance were measured and used to develop predictive equations.

Liou and Morrissey (1985) measured female physiological responses to load carrying with a variety of container widths, container weights and walking speeds on a level treadmill. The data obtained were then compared to data from males performing carrying tasks (Morrissey and Liou, 1984b). Regression models were developed to predict oxygen consumption and heart rate from the knowledge of gender, body weight, load carried, walking speed, and container width. The prediction equations for oxygen consumption and heart rate are provided in Tables 5 and 6.

Evaluation of the models and their limitations

Tables 2–7 summarize the metabolic and cardiac cost prediction models of various MMH tasks. Asfour (1980) and Ayoub *et al.* (1980) pointed out the following limitations of the energy cost prediction models developed by Aberg *et al.* (1968), Chaffin (1967), Frederick (1959), and Garg (1976):

(1) All models are only valid for manual materials handling tasks in the sagittal plane.

(2) They do not take into account the effect of task variables (e.g., frequency, height of handling, box width, and box length) and their interactions.

(3) Subjects were not trained before data collection.

(4) The model developed by Aberg *et al.* (1968) requires the determination of the body's center of gravity, which is difficult to perform.

(5) There is a need to measure the individual's standing metabolic rate in order to apply the models developed by Garg *et al.* (1978).

Asfour (1980) and Ayoub *et al.* (1980) reported that Garg's model for lifting tasks (1976) is the most flexible of all the metabolic rate prediction models developed prior to 1980. However, this model was based on the assumption that the net total metabolic cost of a

Table 5. Energy cost prediction models for carrying tasks.

Source	Dependent variable	Type of task	Model
Garg et al. (1978)	Net metabolic rate (kcal/min)	Carrying loads held at arm's length at sides (in one or both hands)	NMR = 0.8 + O.Q243 * W * V ** 2 + 0.0463 * L * V ** 2 + 0.0462 * L + 0.00379 * (W + L) * TG * V
Garg et al. (1978)	Net metabolic rate (kcal/min)	Carrying loads held against thighs or against waist	NMR = 0.68 + 0.0254 * W * V ** 2 + 0.048 * L * V ** 2 + 0.114 * L + 0.00379 * (W + L) * TG * V
Morrissey and Liou (1984a)	Metabolic rate (watts)	Carrying loads in front of body with both hands	MR = – 181.66 + 7.18 * W + 189.45 * V ** 2 + 3.63 * L * V ** 2 + 0.06 * L * Z – 3.79 * V * (W + L) + 17.76 * (W + L) * (L/W) ** 2
Momssey and Liou (1984b)	Metabolic rate (watts)	Carrying loads in front of body with both hands	MR = – 75.14 + 3.11 * W + V ** 2 * (2.72 * L + 87.75) + 13.36 * (W + L) * ((L/W) ** 2)
Morrissey and Liou (1984c)	Oxygen consumption (l/min)	Carrying loads in front of body with both hands	V02 = 2.74 – 0.03 * P + (L/W) * [0.0016 * V ** 2 * Z – 6.13 * (L/W) + 2.49] + (2.4 * 10 ** – 3) * V * (W + L)
Liou and Morrissey (1985)	Metabolic rate (watts)	Carrying loads in front of body with both hands	MR = 25.4 + 24.1 * 0 + 0.43 * Z * V ** 2 + (W + L) * (3.16 + 2.54 * V ** 2 + 16 * ((L/W) ** 2) – 3.25 * V)

(From Genaidy and Asfour, 1987; reprinted with permission.)

NMR – net metabolic rate for activity performed
MR – metabolic rate
V02 – oxygen consumption
L – load carried (kg)
W – body weight (kg)
TG – treadmill grade level (%)
Z – container width with location of hands in front of body (cm)
P – percent of normal stature
G – gender (male = 1, female = 0)
V – walking speed (km/h)

All models are valid for a duration of less than one hour.

series of activities can be estimated by summing their net steady state individual metabolic costs as obtained from their performance separately. This assumption was reported to be invalid (Asfour, 1980; Genaidy *et al.*, 1985a).

The models developed by Asfour (1980) for lifting and lowering tasks attempted to overcome the limitations of previous models developed prior to 1980. He employed

Table 6. Cardiac cost prediction models for carrying tasks.

Source	Dependent variable	Model
Morrissey and Liou (1984a)	Heart rate (beats/min)	HR – 205.5 + (W + L) * (2.34 * (L/W) + 0.38 * V ** 2 – 0.64 * V – 1.53)
Morrissey and Liou (1984b)	Heart rate (beats/min)	HR = 192 + 27.39 * V * [(V – 1.53) + 1.42(W + L) * (1 – 1.46 * (L/W))]
Morrissey and Liou (1984c)	Heart rate (beats/min)	HR = 227.6 – 16.8 * W + 15.53 * V ** 2 + 13.2 * (L + W) + 0.03 * Z * L – 8.9 * (L/W) * P
Liou and Morrissey (1985)	Heart rate (beats/min)	HR = 113.28 – 10.62 * G + 21.45 * V ** 2 + 2.01 * (W + L) * ((L/W) ** 2) + 0.67 * L * V ** 2 – 0.56 * (W + L) * V

(From Genaidy and Asfour, 1987; reprinted with permission.)

HR – heart rate
L – load carried (kg)
V – treadmill speed (m/sec)
W – body weight (kg)
Z – container width with location of hands in front of body (cm)
P – percentage of normal posture
G – gender (male = 1, female = 0)

All models are valid for a duration of less than one hour.

Table 7. Energy cost prediction models for combined activities.

Source	Type of task	Model
Aberg et al. (1968)	Lifting, lowering, carrying, and dragging	V02 = k1 * W naked + k2 * W with clothing * (k3 * GCBh + k4 * GCBv) + (WWP + WT) * (k5 * Lha + k6 * Mu * Lhc + k7 * Lvu + k8 * Ivd)

(From Genaidy and Asfour, 1987; reprinted with permission.)

V02 – oxygen consumption (1/min)
W – body weight (kg)
GCBh – horizontal displacement per time unit of the body's center of gravity (m/min)
GCBv – vertical displacement per time unit of the body's center of gravity up plus down (m/min)
WWP – weight of work piece (kg)
WT – weight of the tool (kg)
Lha – horizontal displacement per time unit of tool and work piece, arm work (m/min)
Lhc – horizontal displacement per time unit of tool and work piece, carrying or dragging (m/min)
Lvu – upward vertical displacement per time unit of tool and work piece, lifting (m/min)
Lvd – downward vertical displacement per time unit of tool and work piece, lowering (m/min)
Mu – coefficient of friction in horizontal movement
k1 – k7 – constants

All models are valid for a duration of less than one hour.

trained subjects for eight weeks on flexibility, cardiovascular endurance, muscular strength, and muscular endurance (Asfour *et al.*, 1984b). Task variables such as frequency, height, box length, box width, and angle of body twist were incorporated in the models. Based on the database provided by Asfour (1980), Asfour *et al.* (1986a, 1986b), it is apparent that the frequency, load, height, and box size have a significant effect on the energy expenditure of individuals engaged in lifting and lowering tasks.

Morrissey and Liou's models (Liou and Morrissey, 1985; Morrissey and Liou, 1984a, 1984b, 1984c) were developed for carrying boxes with both hands. Their models did not take into account the effect of task variables and their interaction, except for box width. Mital and Asfour (1983) reported that carrying frequency, distance, and height are important parameters in the design of carrying tasks.

The major limitation of most of the models reported in the literature is that they are applicable only to manual tasks of less than 60 minutes duration. Thus, according to Genaidy and Asfour (1987), future models should address the effect of working time on the physiological responses of individuals engaged in MMH tasks.

The models generated by Mital (1983b, 1985) and Mital *et al.* (1984) are the only available models for manual lifting over prolonged periods. These models, however, have some limitations. A low correlation was obtained between task variables and oxygen consumption and heart rate. Mital and coworkers attributed the low correlation to the use of the psychophysical methodology to determine the amount of load that can be handled by individuals. Deivanayagam and Ayoub (1979) indicated that oxygen consumption tends to rise gradually over time while the external work output remained the same. This can be attributed to one of the following factors: a progressive accumulative effect of the products of metabolism; changes in blood flow distribution to various parts of the body other that the working muscles; deterioration in mechanical efficiency; or changes in the constitution of metabolic substrate involved in the energy-release processes.

Many investigators have considered manual materials handling tasks as a continuous type of activity. In fact, an MMH task can be regarded as a pulse function of two to three seconds duration. The gross assumption of a continuous MMH activity does not reflect the metabolic and cardiorespiratory peaks obtained at precisely the moment when the physical pulse loading is applied to the human body. Genaidy *et al.* (1985b) developed the following equations for the working and recovery curves for lowering an 18 kg load at a frequency of 3 times/min from 76 cm above the floor to the floor:

(1) Working curve: heart rate (beats/min) = 93.35 – 20.85*exp(– (time in sec)/1.312).

(2) Recovery curve: heart rate (beats/min) = 92.65*exp(– (time in sec)/67.637).

PSYCHOPHYSICAL 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 obey the psychophysical function where the sensation magnitude S grows as a power function of the stimulus I. Stevens (1975) indicated that the strength of a sensation (S) is directly related to the intensity of its physical stimulus (I) by means of a power function:

$$S = k * I^n \tag{6}$$

Table 8. Net effect of work-related factors on acceptable weight/force.

Factor	MMH activity	Net effect
Frequency (↑)	All	Decrease
Task duration (↑)	All	Decrease
Object size (↑)	All	Decrease
Object shape (various)		
Collapsible (e.g. bags)	Lifting, carrying	Increase
Non-collapsible (e.g. metallic) (volume increases)		Increase
Non-collapsible (volume does not change)		Unknown
Couplings (good)	All	Increase
Load stability/distribution	Lifting, carrying	Decrease
Vertical lift height (↑)	Lifting, lowering	Decrease
Height of force (↑)	Pulling, pushing	Increase
Application/starting point	Lifting, lowering, carrying	Decrease
Distance travelled (↑)	Pushing, pulling, carrying	Decrease
Speed/grade (↑)	Pushing, pulling, carrying	Decrease
Asymmetrical handling	Lifting, lowering	Decrease

(From Mital et al., 1997).

where:

S = strength of a sensation,
I = intensity of physical stimulus,
k = a constant which is a function of the particular units of measurement that are used,
n = the slope of the line that represents the power function when plotted in log-log coordinates. For example, it is equal to 3.5 for electric shock, and 1.6 for the perception of muscular effort and force. Stevens (1975) suggested an 'n' value of 1.45 for lifting weights.

Snook (1978) stated that psychophysics has been applied to practical problems in many areas, such as the scales of effective temperature, loudness and lightness, and ratings of perceived exertion (RPE). To apply the principle of psychophysics to men at work is to utilize the human capability to judge the subjectively perceived strain at work in order to determine voluntarily accepted work stresses. In terms of MMH activities, it can be used to determine what the subject can handle (capacity) without strain or discomfort. As stated by Legg and Myles (1981), with good subject cooperation and firm experimental control, the psychophysical method can identify loads that subjects can lift repetitively for an eight-hour workday without metabolic, cardiovascular or subjective evidence of fatigue. The measure of capacity used in this approach is 'maximum acceptable weight of lift.' Maximum acceptable weight of lift is generally defined as the maximum weight, determined experimentally that a given person could lift repeatedly for long periods of time without undue stress or fatigue.

A number of personal, work, and environmental factors affect the psychophysical design criterion. The details can be found in Ayoub and Mital (1989). Table 8 summarizes the net effect of some of the important work factors.

The psychophysical criterion

The use of psychophysics in the study of lifting tasks requires a subject to adjust the weight of load according to his or her own perception of effort such that the repetitive lifting task does not result in overexertion or excessive fatigue. The final weight selected by the subject is considered to be the maximum acceptable weight (MAW) of lift for the given job conditions (frequency of lift, range of lift, container size, etc.). The MAW is the criterion used for design purposes. Because of the popularity of this approach, it has led to the development of capacity models which can predict lifting capacities (or MAW) for several lifting ranges with a reasonable degree of accuracy and confidence (Asfour, 1980; Asfour *et al.*, 1984a, 1985; Ayoub *et al.*, 1978a, 1983; Karwowski and Ayoub, 1984b; Mital, 1983a, 1983b, 1985).

Psychophysical models

McConville and Hertzberg (1966) investigated the optimum size of a container to be lifted with one hand. Boxes of various sizes (height remained constant) were used. The range of lift was from floor to 76 cm height. They indicated that the weight which 95 per cent of the population would be able to lift could be expressed as a function of object width.

Snook (1976) used data from previous studies by Snook *et al.* (1970) and Snook and Ciriello (1974) to develop a simple model to estimate the object weight to be lifted, based on frequency using a container size of 34 × 48 × 14 cm for floor to knuckle lift. These models are in the form:

$$Y = 14.23 + 5.53\ X \text{ for males} \tag{7}$$

$$Y = 13.64 + 1.6\ X \text{ for females} \tag{8}$$

where:

Y = MAW of lift (kg),
X = frequency of lift in log seconds.

McDaniel (1972) developed a regression model to predict the acceptable weight of lift. The lifting task was defined as the maximum weight the subject was able to lift four times/min for a period of 45 min without strain or unusual fatigue. The range of lift was from the floor to the standing knuckle height of the subject.

Dryden (1973) conducted a similar study to that of McDaniel. The subjects were asked to lift a tote box from their standing knuckle height through a range of 51 cm. The frequency of lift was six lifts/min. Subjects were allowed to adjust their workloads by adding or removing weights from the tote box. A model to predict load of lift was developed using chest circumstance and dynamic endurance as independent variables.

Knipfer (1974) used female and male subjects to develop regression models for prediction of the load of lift. Subjects were asked to lift the box from standing shoulder height through a 51-cm range. The frequency of lift was six lifts/min. The independent variables of the model were back strength, shoulder strength, and age.

Aghazadeh (1974) conducted experiments and also used data by McDaniel (1972), Dryden (1973) and Knipfer (1974) to develop new predictive models. His approach was to establish the relationships between the lifting capacity for lifting from floor to knuckle height and the other two levels of lift, namely, lifting from knuckle height to shoulder height and from shoulder height to reach height. In addition, he included two other task variables —frequency of lift and box size. He simplified the prediction model using the relationship between the levels of lift and considering fewer operator variables and some task and container variables. The simplified model does not have as good an average error ratio as the individual models reported by McDaniel (1972), Dry den (1973) and Knipfer (1974). However, the simplified model has the following advantages (Ayoub and El-Bassoussi, 1976):

(1) One model is used for all three levels of lift.

(2) One model is used for both males and females and such does not have gender as a variable.

(3) The model requires only two measurements of maximum isometric strengths: back strength and leg strength.

Table 9 shows these above-mentioned models, as summarized by Genaidy *et al.* (1988). Tables 10 and 11 give values for C_1, C_2, and C_3 for the models developed by Aghazadeh.

Ayoub *et al.* (1978b) conducted a study using industrial subjects to generate capacity data. Based on those data predictive models for the working population as well as individuals for different height levels as a function of operator and task variables were developed. Six different levels of lift were utilized (floor to knuckle, floor to shoulder, knuckle to shoulder, knuckle to reach, and shoulder to reach height) at rates of two, four, six and eight lifts/min. Three different box sizes were: 12 × 7 × 12, 12 × 7 × 18, and 12 × 7 × 24 (width × depth × length, in). Various strength and anthropometric measurements were recorded for each subject. A stepwise linear regression analysis was employed to select the best prediction model. These models estimated an individual's lifting capacity.

Mital and Ayoub (1980) improved on the predictive models for lifting from data developed by Ayoub *et al.* (1978a). These models, in the form of regression equations, predicted an individual's MAW by using isometric strengths and personal characteristics (age, sex, and anthropometric variables). These revised models are shown in Table 12. Table 13 shows the multipliers to correct the predicted lift from the models for frequencies ranging from one to eight lifts/min.

Asfour (1980) proposed psychophysical lifting/lowering capacity models for two height ranges (start at floor or at 30 in above the floor). The variables incorporated in the models were the subject's body weight, frequency of lift, box size (width and length), and angle of body twist.

Garg and Ayoub (1980) conducted a psychophysical study to develop lifting capacity models by using a single strength (static or dynamic) variable. These models are attractive because of their simple form. They showed that the static vertical lift strength measured at the origin of lift significantly underestimated the dynamic lifting capacity as determined by psychophysical methodology. When the static vertical lift strength was performed closer to the body, such a bias was eliminated. They concluded that specific static strength tests must be carefully constructed to predict accurately a person's dynamic lifting capacity.

The arguments against lifting capacity models based on static strength tests are that actual lifting is dynamic in nature although temporary static components are involved (Aghazadeh and Ayoub, 1985; Kamon *et al.*, 1982). Consequently, dynamic strength

Table 9. Summary of psychophysical models.

Researchers	Dependent variables	Height level	Male	Female	Both	Model
McConville and Hertzberg (1966)	Maximum weight of lift *	Floor to knuckle	X			Predicted lift = 60 – (width of box in inches
Poulsen (1970)	Maximum weight of lift	Floor to table			X	Predicted lift = 1.40 (max. isometric back st.) – 0.50 (body wt)
		Table to head			X	Predicted lift = 0.50 (sum of right and left max. isometric arm push)
McDaniel (1972); Ayoub and El-Bassoussi (1976)	Load of lift **	Floor to knuckle	X			Predicted lift = 172.36 + 0.02 $(ht)^2$ – 2.73 (static $end.)^2$ + 0.02 (RPI) (arm st.) + 0.05 (RPI) (back st.) – 2.51 (Fl/dynamic end.)
	Load of lift	Floor to knuckle		X		Predicted lift = – 24.03 + $0.19(RPI)^2$ + 0.006 (arm st.) (leg st.)
	Load of lift	Floor to knuckle			X	Predicted lift = 11.93 – 1.12 (back st.) + 0.16 $(RPI)^2$ + 0.005 $(back\ st.)^2$ – 8.81 $(static\ end.)^2$ – 0.1 (sex) (Fl) + 0.06(ht) (RPI) + 0.03 (RPI) (leg st.) – 0.002 (back st.) (leg st.) – 0.03 (leg st.) (stat. end.) + 0.11 (static end.) (Fl)
Dryden (1973)	Load of lift	Knuckle to shoulder	X			Predicted lift = 0.0 + 0.83 (chest circumference) + 0.56 (dynamic end.)
Ayoub and El-Bassoussi (1976)	Load of lift	Knuckle to shoulder		X		Predicted lift = 0.0 + 3.81 (RPI) – 1.47(ht) (F1/1000) – 0.31 (RPI) (static end.) + 1.23 (percent fat) (F1/1000)
	Load of lift	Knuckle to shoulder			X	Predicted lift = 25.12 + 0.38 (sex) (dynamic end.)
Knipfer (1974)	Load of lift	Shoulder to reach	X			Predicted lift = 4.91 + 0.2 (back st.) – 0.02 (shoulder st.) + 0.43 (age)
Aghazadeh (1974)	Load of lift	Floor to knuckle, knuckle to shoulder, shoulder to reach	X			Predicted lift = $(C_1S + C_2)C_3$ (C_1, C_2 = factor of freq. and height of lift; S = (back st. × leg st.)/1000
Ayoub and El-Bassoussi (1976)	Load of lift	Shoulder to reach		X		Predicted lift = 0.34 (wt) + 0.84 (dynamic end.) + 0.34 (forearm circumference)
	Load of lift	Shoulder to reach			X	Predicted lift = 5.23 (sex) + 0.005 (shoulder st.) + 0.19 (horizontal push st.)
	Load of lift	Floor to knuckle, knuckle to shoulder, shoulder to reach			X	Predicted lift = 13.19 + 13.85 (sex) + 0.26 (dynamic end.)

Table 9 (Continued).

Researchers	Dependent variables	Height level	Male	Female	Both	Model
Ayoub et al. (1978a)	Load of lift + body weight	Floor to knuckle			X	Predicted lift = – 72.17 – 28.33 (sex) + 24.24 (wt code) + 0.14 (arm st.) – 0.55 (age) + 1.23 (shoulder ht) + 0.06 (back st.) + 4.91 (abdominal depth) + 1.76 (dynamic end.)
	Load of lift + body weight	Floor to shoulder			X	Predicted lift = 145.41 – 16.17 (sex) + 11.93 (wt code) + 0.19 (arm st.) – 0.6 (age) + 1.44 (shoulder ht) + 0.08 (back st.) + 6.47 (abdominal depth) + 2.61 (dynamic end.)
	Load of lift + body weight	Floor to reach			X	Predicted lift = – 41.27 – 19.45 (sex) + 16.18 (wt code) + 0.21 (arm st.) – 0.84 (age) + 0.76 (shoulder ht) + 0.07 (back st.) + 6.22 (abdominal depth) + 1.43 (dynamic end.)
	Load of lift + body weight	Knuckle to shoulder			X	Predicted lift = – 55.16 – 18.45 (sex) + 11.70 (wt code) + 0.27 (arm st.) – 0.61 (age) + 0.77 (shoulder ht) + O.H (back st.) + 6.29 (abdominal depth) + 1.42 (dynamic end.)
	Load of lift + body weight	Knuckle to reach			X	Predicted lift = – 79.19 – 18.92 (sex) + 17.27 (wt code) + 0.3 (arm st.) – 0.5 (age) + 1.09 (shoulder ht) + 0.02 (back st.) + 5.15 (abdominal depth) + 2.12 (dynamic end.)
	Load of lift + body weight	Shoulder to reach			X	Predicted lift = – 37.44 – 19.58 (sex) + 20.35 (wt code) + 0.1 (arm st.) – 0.6 (age) + 0.89 (shoulder ht) + 0.1 (back st.) + 4.73 (abdominal depth) + 1.09 (dynamic end.)

(From Ayoub et al., 1980; reprinted with permission.

RPI = (body ht) ÷ (body wt)$^{1/3}$

F1 = 100 × duration of the step exercise (s)/2 x pulse recovery sum

* Maximum weight subjects could lift for non – repetitive lifting

** Maximum weight subjects were willing to lift for repetitive lifting

Lift ht* = 127 cm for floor to shoulder and 76 for shoulder to shoulder

See Table 10 for C_1 and C_2; see Table 11 for C_3.

Table 10. Factors for predicting acceptable amount of lift for different heights at different frequencies.

Frequency		C_1	C_2
		Knuckle height	
Frequency of	1	1.87	20.1
	2	1.77	19.1
	3	1.66	17.9
	4	1.57	16.9
	5	1.48	15.9
	6	1.37	14.7
		Shoulder height	
Frequency of	1	2.49	43.6
	2	2.37	33.9
	3	2.22	29.5
	4	2.09	26.7
	5	1.97	24.6
	6	1.82	22.4
		Reach height	
Frequency of	1	1.87	25.1
	2	1.79	26.8
	3	1.68	23.0
	4	1.57	20.6
	5	1.48	18.9
	6	1.37	17.2

(From Ayoub et al., 1978b).

Table 11. Factors for box size.

Box length (dimension in sagittal plane)	Box size factor, C_3
10	1.00
12	0.98
14	0.95
16	0.93
18	0.90
20	0.88
22	0.86
24	0.83
26	0.81
28	0.78
30	0.76

(From Ayoub et al., 1978a).

should play a more important role in lifting than static strength. In recent years, several researchers have developed psychophysical lifting capacity models based on dynamic strength tests.

Pytel and Kamon (1981) adapted a portable commercially available device ('Mini-Gym,' model 101) to measure isokinetic dynamic strength. A lifting experiment was de-

Table 12. Coefficients for models for predicting maximum acceptable weight of lift (MAW) plus body weight (pounds).

Height of lift	Constant term	Sex code*	Arm st.	Age	Shoulder ht.	Back . st.	Abdominal depth	Dynamic end.	(Arm st.)^2	(Age)^2
FK	-19.444	-15.630	1.051	-0.661	–	0.448	–	10.250	-0.004	–
FS	-108.770	-7.109	1.372	-1.894	–	–	7.685	14.809	-0.007	0.016
FR	-850.993	–	1.449	-2.253	10.687	0.078	8.026	18.193	-0.007	0.018
KS	-148.125	-6.688	1.521	-2.161	1.015	–	7.658	14.881	-0.008	0.020
KR	-194.177	-6.679	1.394	-2.011	1.391	–	7.129	18.460	-0.006	0.017
SR	-904.215	–	0.964	-0.759	10.131	0.110	15.026	18.078	-0.004	–

Height of lift	Shoulder height^2	Back strength^2	Abdominal depth^2	Dynamic end.^{2}	Mean W (males)	Mean W (females)	Mean error (W) (pre.-actual)	SD of error in W	Std. error of mean for W	R^2
FK	0.004	-0.001	0.146	-1.213	61.170	37.120	-8.620	20.630	2.360	0.850
FS	0.005	0.0003	-	-1.682	51.210	21.080	-0.120	19.800	2.490	0.903
FR	-0.034	–	-	-1.945	29.120	28.140	2.610	23.280	2.880	0.877
KS	-	0.0004	-	-1.598	54.470	31.970	-4.910	22.100	2.530	0.893
KR	-	-0.0004	-	-1.988	53.540	26.220	-7.460	19.590	2.260	0.902
SR	-0.031	–	-0.174	-1.915	42.620	25.780	12.080	20.680	2.350	0.873

(From Mital and Ayoub, 1980; reprinted with permission.
Note: Age is in years; strengths (arm and back) are in pounds; body dimensions are in centimetres; dynamic endurance is in minutes.
* Sex code: 0 for males; 1 for females
FK: floor to knuckle; FS: floor to shoulder; FR: floor to reach; KS: knuckle to shoulder; KR: knuckle to reach; SR: shoulder to reach.

Table 13. Multipliers to adjust the maximum acceptable weight of lift for frequency.

Height of lift	Sex	Frequency (lifts/min) 1	2	4	5	6	8
Floor to knuckle	Male	1.093	1.067	1.015	1.0	0.985	0.934
	Female	1.214	1.134	1.053	1.0	0.946	0.785
Floor to shoulder	Male	1.081	1.056	1.008	1.0	0.992	0.934
	Female	1.165	1.113	1.007	1.0	0.992	0.975
Floor to reach	Male	1.126	1.089	1.016	1.0	0.984	0.827
	Female	1.144	1.106	1.030	1.0	0.970	0.956
Knuckle to shoulder	Male	1.110	1.074	1.002	1.0	0.984	0.930
	Female	1.280	1.210	1.070	1.0	0.930	0.790
Knuckle to reach	Male	1.244	1.172	1.028	1.0	0.971	0.895
	Female	1.017	1.009	1.008	1.0	0.991	0.935
Shoulder to reach	Male	1.071	1.059	1.036	1.0	0.964	0.874
	Female	1.196	1.147	1.049	1.0	0.950	0.901

(From Mital and Ayoub, 1980; reprinted with permission.)

Table 14. Prediction models developed by Kamon et al. (1982).

LC = 1.04 * EF + 330; r = 0.49
LC = 1.65 * ES + 251; r = 0.47
LC = 0.46 * BE + 380; r = 0.51
LC = 0.54 * LS + 304; r = 0.47
IL = 0.96 * BE + 254; r = 0.65

where:

LC = lifting capacity (Newtons)
EF = elbow flexion, maximal contraction one arm
ES = elbow strength, dynamic flexion of two arms (isokinetic strength)
BE = back extension, maximum voluntary contraction
IL = isometric lift, static simulated lift
LS = lifting strength, simulated dynamic lift motion

signed to lift a tote box (44 cm × 30 cm × 12 cm) with handles from the floor to 113 cm height. A simple psychophysical model was developed using a simple strength test procedure, a concise form of the prediction models. However, R^2 values were relatively low in this study. Only one lifting range (floor to 113 cm height) and one lifting frequency were studied.

Kamon *et al.* (1982) employed the same test procedure as Pytel and Kamon (1981) to test 228 male steelmill workers. Two psychophysical lifting models were developed by using a single static strength measure (back extension maximum voluntary contraction) or a single dynamic strength measure (lifting strength). The generated models are in the form of linear regression equations as shown in Table 14.

Aghazadeh (1983) studied the relationship between box/bag lifting capacity and the subject's strength test. Three task-related variables and five operator-related variables

Table 15. Prediction models for the maximum acceptable weight of lift using dynamic strength.

Model code	Constant term	CONTAINR coefficient	LIFTTYPE coefficient	FRQNCY coefficient	DYNSTKS coefficient	R^2
BXBDG	54.72	– 9.68	– 0.11	– 2.21	0.27	0.726
BGD	43.18	–	– 0.18	– 1.91	0.21	0.594
BXD	37.21	–	– 0.03	– 2.52	0.34	0.775
BXBGDKS	41.37	– 7.52	–	– 2.21	– 0.36	0.778
BXBGDFS	51.02	– 9.68	–	– 2.21	0.27	0.706
BGDKS	29.94	–	–	– 1.87	0.30	0.725
BGDFS	43.96	–	–	– 1.94	0.11	0.452
BXDKS	30.24	–	–	– 2.55	0.41	0.795
BXDFS	41.82	–	–	– 2.49	0.27	0.798

(From Aghazadeh, 1983).
Container code: CONTAINR = 1 for box and 2 for bag
Lift type code: LIFTTYPE = 20 for knuckle to shoulder height lift and 50 for floor to shoulder height lift
Frequency code: FRQNCY = 2 for 2 lifts/min and 6 for 6 lifts/min
Knuckle to shoulder dynamic strength code: DYNSTKS, units are in foot pounds
General models for box and bag lifting (code BXBGD)
Models for bag lifting only (code BGD)
Models for box lifting only (code BXD)
Models for box and bag lifting from knuckle to shoulder height (code BXBGDKS)
Models for box and bag lifting from floor to shoulder height (code BXBGDFS)
Models for bag lifting from knuckle to shoulder height (code BGDKS)
Models for bag lifting from floor to shoulder height (code BGDFS)
Models for box lifting from knuckle to shoulder height (code BXDKS)
Models for box lifting from floor to shoulder height (code BXDFS).

were studied. Task variables were container type (bag or box), frequency of lift (two or six lifts/min) and lifting ranges floor to shoulder and knuckle to shoulder (FS and KS). Operator-related variables were static strength (arm, stooped back, standing back, composite, shoulder and leg), dynamic strength measured using Cybex isokinetic strength equipment (FS and KS), endurance (static and dynamic), PWC, subject's height and weight. Nine dynamic models and nine static models were developed (see Table 15). Both static models and dynamic models could predict the maximum acceptable lifting capacity with a reasonable degree of accuracy (R^2 with the range of 0.452 to 0.862). Aghazadeh and Ayoub (1985) developed models for prediction of weight lifting capacity of individuals incorporating static strengths and dynamic strengths of the individual in a simulated lifting position and task variables: height and frequency of lift. It was concluded that both the dynamic and static models could predict the maximum acceptable amount of lift with a reasonable degree of accuracy. The use of the dynamic model resulted in less absolute error between the actual and predicted load than the static model (reduction of 44 per cent).

Jiang (1984) developed prediction models for both individual and combined MMH activities and examined the relationship between individual and combined MMH activities. MMH capacity was defined as the maximum weight the subject was willing to handle plus his or her body weight for a period of one hour under the variable task conditions.

Each activity was conducted under three different frequencies: one time maximum, one handling per min, and six handlings per min. The prediction models for the capacities of individual MMH activities were developed based on the isoinertial six feet weight incremental lifting test or the isometric back strength test. The isoinertial 6-ft incremental weight lifting test was proved to be the best predictor for the individual MMH activities. Since this type of strength test involved both static strength to overcome the inertial resistance and dynamic strength to move the weight to a pre-assigned location, it was recommended as the most promising single screening test.

Jiang *et al.* (1986) developed models to predict capacity for combined material handling activities. Four individual MMH activities were studied: lifting from floor to knuckle height (LFK); lifting from knuckle to shoulder height (LKS); lowering from knuckle to floor height (LOW); and carrying for 3.4 m (C). Three combined MMH activities were studied: lifting from floor to knuckle height and carrying 3.4 m (LC); lifting from floor to knuckle height, carrying 3.4 m, and lifting from knuckle to shoulder height (LCL); and lifting from floor to knuckle height, carrying 3.4 m, and lowering from knuckle to floor height (LCLO).

Three different approaches were used for the modeling of combined MMH capacities: modeling based on one limiting individual MMH capacity, modeling based on isoinertial 1.83 m maximum strength, and modeling based on fuzzy-set theory (the fuzzy-set theory model will be omitted from this discussion). Models were developed using simple and multiple regression, and were evaluated according to goodness of fit (in terms of R^2 values) and PRESS statistics. Both advantages and disadvantages were found for both model types. Unfortunately, these models have yet to be fully validated.

The basis for the *first* approach uses the limiting individual MMH capacity as a predictor. The limiting capacity usually occurs at the most stressful individual activity (or at the weakest joint of the body) used in handling the task. The limiting activity was derived from the minimal capacity of all the individual capacity elements that made up the MMH task. The individual models (for each of the three combined MMH activities —at each of the three frequency conditions) and their corresponding limiting activity and R^2 values are shown in Table 16.

The key advantage of these limiting activity-based models is found in the incredibly high R^2 values. Thus, these models had the best fit to the experimental data, in terms of R^2 values. As a result, if the limiting individual MMH capacity is known, the combined MMH capacity can be predicted accurately, using the individual MMH capacity. The close relationship between combined activity and limiting individual activity provides a good framework for job design/redesign that involves combined MMH activity. Several disadvantages exist, however. First, the relationship between combined and individual limiting capacities has not been developed. Next, in order to have the best predicted results, these models should only apply within the range of the independent variables used in this study. Furthermore, it should be again noted that this study only encompassed the participation of 12 (male) subjects, a small sample. Finally, the testing procedure for limiting individual activities should follow the testing procedure used in this study.

The basis for the *second* approach uses isoinertial strength of lifting from floor to a height of 1.83 m (this isoinertial strength test will be denoted at T1). The principle involved in the modeling came from an effort to match an individual's physical condition to his MMH capacities. These models were developed and selected according to simplicity, goodness of fit, and representation of variables. Table 17 shows the individual models

Table 16. Combined activity models by Jiang et al. (1986).

Combined activity	R^2	Limiting activity
LCM = 0.762 + (0.953 – LFKM)	0.952	LFKM
LCLM = 3.015 + (0.973 * LKSM)	0.967	LKSM
LCLOM = – 17.805 + (1.602 * LFKM)	0.966	LFKM
LC1 = 16.903 + (0.809•1[LFK1)	0.980	LFK1
LCL1 = – 4.201 + (1.022 * LKS1)	0.963	LKS1
LCL01 = 27.777 + (0.685 * LFK1)	0.915	LFK1
LC6 = – 1.449 + (0.969 * LFK6)	0.941	LFK6
LCL6 = 7.126 + (0.883 * LKS6)	0.932	LKS6
LCL06 = 6.272 + (0.867 * LFK6)	0.920	LFK6

Lifting F – K (LFK):
- LFKM – LFK at the frequency of one time maximum
- LFK1 – LFK at the frequency of 1 handling/min
- LFK6 – LFK at the frequency of 6 handlings/min

Lifting K – S (LKS):
- LKSM – LKS at the frequency of one time maximum
- LKS1 – LKS at the frequency of 1 handling/min
- LKS6 – LKS at the frequency of 6 handlings/min

Lowering K – S (LOW):
- LOWM – LOW at the frequency of one time maximum
- LOW1 – LOW at the frequency of 1 handling/min
- LOW6 – LOW at the frequency of 6 handlings/min

Two hand front carrying for 14 feet (C):
- CM – C at the frequency of one time maximum
- Cl – C at the frequency of 1 handling/min
- C6 – C at the frequency of 6 handlings/min

Lifting F – K + carrying 14 ft (LC):
- LCM – LC at the frequency of one time maximum
- LC1 – LC at the frequency of 1 handling/min
- LC6 – LC at the frequency of 6 handlings/min

Lifting F – K + carrying 14 ft + lifting K–S (LCL):
- LCLM – LCL at the frequency of one time maximum
- LCL1 – LCL at the frequency of 1 handling/min
- LCL6 – LCL at the frequency of 6 handlings/min

Lifting F – K + carrying 14 ft + lowering K–F (LCLO):
- LCLOM – LCLO at the frequency of one time maximum
- LCL01 – LCLO at the frequency of 1 handling/min
- LCL06 – LCLO at the frequency of 6 handlings/min

for each of the three combined MMH activities at each of the three frequency conditions and their corresponding R^2 and PRESS values.

Some of the advantages of isoinertial strength-based models include: (1) combined MMH capacities can be predicted by simple strength testing which can be conducted in less than five minutes; (2) the combined MMH capacity can be predicted from strength testing, directly; (3) no knowledge of individual capacities is required; and (4) the isoinertial strength tests are more representative of actual industrial lifting activities than other tests. The disadvantages of isoinertial strength-based models are very similar to those dis-

Table 17. Models to predict combined activities using 6 ft incremental lift test.

The models		R^2
LCM	= 129.749 – (1.642 * T1) + (0.029249 * $T1^2$)	0.913
LCLM	= 165.945 – (2.545 * T1) + (0.028413 * $T1^2$)	0.885
LCLOM	= 126.811 – (1.884 * T1) + (0.033231 * $T1^2$)	0.916
LC1	= 144.735 – (2.312 * T1) + (0.027586 * $T1^2$)	0.947
LCL1	= 75.280 – (0.009 * T1) + (0.007132 * $T1^2$)	0.854
LCL01	= 139.556 – (2.092 * T1) + (0.024567 * $T1^2$)	0.923
LC6	= 99.641 – (1.042 * T1) + (0.015411 * $T1^2$)	0.790
LCL6	= 98.427 – (0.999 * T1) + (0.014337 * $T1^2$)	0.811
LCL06	= 120.787 – (1.734 * T1) + (0.020301 * $T1^2$)	0.846

(From Jiang et al., 1986).

advantages presented above, for the limiting-activity-based models. First, a small sample size of 12 subjects was used to develop the above models. Also, the application of these models should be within the range of the T1 values used in this study (47.7–79.5 kg). Finally, the testing procedure using T1 in this study should be followed in order to measure the isoinertial strength of T1.

Most MMH prediction models have focused on lifting activities. Few models however were developed to predict capacity for lowering, pushing, pulling, and carrying tasks. These are briefly presented in Tables 18, 19, 20, and 21.

All of the models presented above can be used to predict individual capacities. Models to estimate population capacities have also been developed. Ayoub *et al.* (1983) developed population models to estimate the lifting capacities for the various percentiles of the population. These models were based on the data generated by Ayoub *et al.* (1978a) (see earlier section for more details on the variables in the study). Table 22 shows these models for both males and females.

CONFLICTS BETWEEN CRITERIA BASED ON THE VARIOUS APPROACHES

It is not surprising that criteria based on the principles of biomechanics, psychophysics, and physiology often provide MMH limits that are in conflict. These conflicts pose confusion for practitioners, and make selecting a proper limit troublesome. An example of the conflicts between the criteria is shown in Figure 3, which illustrates recommended loads as a function of frequency for a floor to shoulder lift. The example is based on Kirn's (1990) models using a 650 kg spinal compression limit and a 1 l/min physiological criteria for males. The biomechanical approach results in high-recommended weights for high-frequency tasks and the physiological approach results in high-recommended loads at low frequencies. The figure also illustrates how the psychophysical approach may be in conflict with the physiological approach. The most conservative approach to these conflicts is to consider all criteria simultaneously in order to estimate the recommended weight for lift as was proposed by Kim (1990). The NIOSH equations of 1981 and 1991 use an approach considering all three criteria to estimate the recommended weight limit (RWL).

Table 18. Lowering capacity prediction models.

Source	Height of lower	Gender	Model	R^2
Asfour (1980)	HL1	Male	LC = 7.2904 – 0.4887 * (10 ** –6) * BS1 * BS2 * AT * F * HL1 + 613153.53 * (10 ** – 6) * BW – 145.03 * (10 ** – 6) * BS * (F ** 3)	0.72
	HL2	Male	LC = 0.9868 – 48.2692 * (10 ** – 6) * F * BS1 * BS2 * AT + 367670.51 * (10 ** – 6) * BS – 65.25 * (10 ** – 6) * BW * (F ** 3)	0.70
Mital (1983c)	All	Both	LC = 15.12 – 7.85 * (1/BS1) + 131.53 * (1/HL3) – 0.092 * (1/F) – 2.75 * LN(F) + 1.58 * G * HL + 0.344 * G * F + 0.034 * BS1 * HL + 0.002 * HS3 * F + 0.33 * HL * F	0.94

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HL1: height of lower above the floor (cm)
HL2: height of lower above table height (cm)
LC: lowering capacity (kg)
BS1: box length (cm)
BS2: box width (cm)
AT: angle of twist (dge)
F: frequency of lower (times/min)
BW: body weight (kg)
G: gender (G = 0 for male and 1 for female)
HL: height of lower (HL = 1 for floor to knuckle, 2 for knuckle to shoulder, and 3 for shoulder to reach)
HL3: vertical distance of lower (cm).

The model developed by Mital (1983c) was based on the data generated by Snook (1978); all models are applicable only for the free – style lifting technique.

Table 19. Pushing capacity prediction models.

Source	Gender	Model	R^2
Mital (1983c)	Male	PC = 17.29 – 0.166 * HD – 11.45 * F + 0.0013 * (HD ** 2) + 5.60 * (F ** 2) + 0.001 * (1/F) + 0.047 * HD * F	0.968
	Female	PC = 10.31 – 0.133 * WD – 16.15 * F – 0.154 * LN(F) + 6.17 * EXP(F) + 0.056 * HD * F	0.960

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PC: pushing capacity (kg)
HD: horizontal distance of push (m)
F: frequency of push (times/min).

The model developed by Mital (1983c) was based on the data generated by Snook (1978).

Table 20. Pulling capacity prediction models.

Source	Gender	Model	R^2
Mital (1983c)	Male	PC = 18.48 – 0.685 * F – 0.0003 * (VD ** 2) + 0.003 * VD * F – 0.5 * LN(F)	0.978
	Female	PC = 15.03 – 0.394 * F – 0.0003 * (VD ** 2) – 0.331 * LN(F)	0.945

(From Genaidy et al., 1988; reprinted with permission.)

PC: pulling capacity (kg)
VD: vertical distance of pull (m)
F: frequency of pull (times/min).

The model developed by Mital (1983c) was based on the data generated by Snook (1978).

Table 21. Carrying capacity prediction models.

Source	Gender	Model	R^2
Mital (1983c)	Male	CC = 77.27 – 12.46 * LN(VD) – 2.4 * LN(HD) – 0.011 * (1/F) – 2.01 * LN(F)	0.962
	Female	CC = 46.49 – 0.239 * HD – 7.12 * LN(VD) – 0.0073 * (l/F) – 1.44 * LN(F) + 0.0003 * VD * HD * F	0.955

(From Genaidy et al., 1988; reprinted with permission.)

CC: carrying capacity (kg)
VD: height at which load is carried (cm)
F: frequency of carry (times/min)
HD: horizontal distance of cany (m).

The model developed by Mital (1983c) was based on the data generated by Snook (1978).

Table 22. Lifting capacity prediction models.

Gender	Height of lift	Frequency (times/min)	Box size	Model
Male	F–K	0.1 < F < 1.0	12 < BS < 18	LC = [57.2 * F ** (– 0.184697)] + [1.65 * (18 – BS)] + [Z * 16.86 * F ** (– 0.174197)]
	F–K	0.1 < F < 1.0	BX > 18	LC – [57.2 * F ** (– 0.184697)] + [0/8 * (18 – BS)] + [Z * 16.86 * F ** (– 0.174197)]
	F–K	1.0 < F < 12.0	12 < BS < 18	LC = [57.2 – 2.0 * (F – 1)] + [1.65 * (18 – BS)] + [Z * (16.86 – 0.5943 * (F – 1))]
	F–K	1.0 < F < 12.0	BS > 18	LC = [57.2 – 2.0 * (F – 1)] + [0.8 * (18 – BS)] + [Z * (16.86 – 0.5964 * (F – 1))]
Male	F–S	0.1 < F < 1.0	12 < BS < 18	LC = [51.2 * F ** (– 0.184697)] + [1.65 * (18 – BS)] + [Z * 15.09 * F ** (– 0.174197)]
	F–S	0.1 < F < 1.0	BS > 18	LC = [51.2 * F ** (– 0.184697)] + [0.8 * (18 – BS)] + [Z * 15.09 * F ** (– 0.174197)]
	F–S	1.0 < F < 12.0	12 < BS < 18	LC = [51.2 – 2.0 * (F – 1)] + [1.65 * (18 – BS)] + [Z * (15.09 – 0.5338 * (F – 1))]
	F–S	1.0 < F < 12.0	BS > 18	LC = [51.2 – 2.0 * (F – 1)] + [0.8 * (18 – BS)] + [Z * (15.09 – 0.5338 * (F – 1))]

Table 22 (Continued).

Gender	Height of lift	Frequency (times/min)	Box size	Model
Male	F–R	0.1 < F < 1.0	12 < BS < 18	LC = [49.1 * F ** (– 0.184697)] + [1.65 * (18 – BS)] + [Z * 14.47 * F ** (– 0.174197)]
	F–R	0.1 < F < 1.0	BS > 18	LC = [49.1 * F ** (– 0.184697)] + [0.8 * (18 – BS)] + [Z * 14.47 * F ** (– 0.174197)]
	F–R	1.0 < F < 12.0	12 < BS < 18	LC – [49.1 – 2.0 * (F – 1)] + [1.65 * (18 – BS)] + [Z * (14.47 – 0.5119 * (F – 1))]
	F–R	1.0 < F < 12.0	BS > 18	LC = [49.1 – 2.0 * (F – 1)] + [0.8 * (18 – BS)] + [Z * (14.47 – 0.5119 * (F – 1))]
Male	K–S	0.1 < F < 1.0	12 < BS < 18	LC = [52.8 * F ** (– 0.138650)] + [1.10 * (18 – BS)] + [Z * 14.67 * F ** (– 0.156762)]
	K–S	0.1 < F < 1.0	BS > 18	LC = [52.8 * F ** (– 0.138650)] + [0.8 * (18 – BS)] + [Z * 14.67 * F ** (– 0.156762)]
	K–S	1.0 < F < 12.0	12 < BS < 18	LC = [52.8 – 2.0 * (F – 1)] + [1.10 * (18 – BS)] + [Z * (14.67 – 0.5534 * (F – 1))]
	K–S	1.0 < F < 12.0	BS > 18	LC = [52.8 – 2.0 * (F – 1)] + [0.8 * (18 – BS)] + [Z * (14.67 – 0.5534 * (F – 1))]
Male	K–R	0.1 < F < 1.0	12 < BS < 18	LC = 50.0 * F ** (– 0.138650)] + [1.10 * (18 – BS)] + [Z * 13.89 * F * •lt(– 0.156762)]
	K–R	0.1 < F < 1.0	BS > 18	LC = [50.0 * F ** (– 0.138650)] + [0.8 * (18 – BS)] + [Z * 13.89 * F ** (– 0.156762)]
	K–R	1.0 < F < 12.0	12 < BS < 18	LC = [50.0 – 2.0 * (F – 1)] + [I.IO * ^ – BS)] + [Z * 13.89 – 0.5240 * (F – 1))]
	K–R	1.0 < F < 12.0	BS > 18	LC = [50.0 – 2.0 * (F – 1)] + [0.8 * (18 – BS)] + [Z * 13.89 – 0.5240^ – 1))]
Male	S–R	0.1 < F < 1.0	12 < BS < 18	LC = [48.4 * F ** (– 0.138650)] + [1.10 * (18 – BS)] + [Z * 13.45 * F ** (– 0.156762)]
	S–R	0.1 < F < 1.0	BS > 18	LC = [48.4 * F ** (– 0.138650)] + [0.8 * (18 – BS)] + [Z * 13.45 * F ** (– 0.156762)]
	S–R	1.0 < F < 12.0	12 < BS < 18	LC = [48.4 – 2.0 * (F – 1)] + [1.10 * (18 – BS)] + [Z * (13.45 – 0.5074 * (F – 1))]
	S–R	1.0 < F < 12.0	BS > 18	LC = [48.4 – 2.0 * (F – 1)] + [0.8 * (18 – BS)] + [Z * (13.45 – 0.5074 * (F – 1))]
Female	F–K	0.1 < F < 1.0	12 < BS < 18	LC = [37.4 * F ** (– 0.187818)] + [1.10 * (18 – BS)] * [Z * 6.87 * F ** (– 0.251605)]
	F–K	0.1 < F < 1.0	BS > 18	LC – [37.4 * F ** (– 0.187818)] + [0.4 * (18 – BS)] + [Z * 6.87 * F ** (– 0.251605)]
	F–K	1.0 < F < 12.0	12 < BS < 18	LC = [37.4 – 1.1 * (F – 1)] + [1.10 * (18 – BS)] + [Z * (6.87 – 0.1564 * (F – 1))]
	F–K	1.0 < F < 12.0	BS > 18	LC = [37.4 – 1.1 * (F – 1)] + [0.40 * (18 – BS)] + [Z * (6.87 – 0.1564 * (F – 1))]
Female	F–S	0.1 < F < 1.0	12 < BS < 18	LC = [31.1 * F ** (– 0.187818)] + [1.10 * (18 – BS)] + [Z * 5.71 * F ** (– 0.251605)]
	F–S	0.1 < F < 1.0	BS > 18	LC = [31.1 * F ** (– 0.187818)] + [0.4 * (18 – BS)] + [Z * 5.71 * F ** (– 0.251605)]
	F–S	1.0 < F < 12.0	12 < BS > 18	LC = [31.1 – 1.1 * (F – 1)] + [1.10 * (18 – BS)] + [Z * (5.71 – 0.1300 * (F – 1))]
	F–S	1.0 < F < 12.0	BS > 18	LC = [31.1 – 1.1 * (F – 1)] + [0.4 * (18 – BS)] + [Z * (5.71 – 0.1300 * (F – 1))]

Table 22 (Continued).

Gender	Height of lift	Frequency (times/min)	Box size	Model
Female	F–R	0.1 < F < 1.0	12 < BS < 18	LC = [28.1 * F ** (– 0.187818)] + [1.10 * (18 – BS)] + [Z * 5.16 * F ** (– 0.251605)]
	F–R	0.1 < F < 1.0	BS > 18	LC = [28.1 * F ** (– 0.187818)] + [0.4 * (18 – BS)] + [Z * 5.16 * F ** (– 0.251605)]
	F–R	1.0 < F < 12.0	BS > 18	LC = [28.1 – 1.1 * (F – 1)] + [0.4 * (18 – BS)] + [Z * (5.16 – 0.1175 * (F – 1))]
Female	K–S	0.1 < F < 1.0	12 < BS < 18	LC = [30.8 * F ** (– 0.156150)] + [0.55 * (18 – BS)] + [Z * 5.66 * F * •lt(– 0.258700)]
	K–S	0.1 < F < 1.0	BS > 18	LC = [30.8 * F ** (– 0.156150)] + [0.2 * (18 – BS)] + [Z * 5.66 * F ** (– 0.258700)]
Female	K–S	1.0 < F < 12.0	12 < BS < 18	LC = [30.8 – 1.1 * (F – 1)] + [0.55 * (18 – BS)] + [Z * (5.66 – 0.1289 * (F – 1))]
	K–S	1.0 < F < 12.0	BS > 18	LC = [30.8 – 1.1 * (F – 1)] + [0.2 * (18 – BS)] + [Z * (5.66) – 0.1289 * (F – 1))]
Female	K–R	0.1 < F < 1.0	12 < BS < 18	LC = [27.3 * F ** (– 0.156l50)] + [0.55 * (18 – BS)] + [Z * 5.01 * F ** (– 0.258700)]
	K–R	0.1 < F < 1.0	BS > 18	LC = [27.3 * F ** (0.156150)] + [0.2 * (18 – BS)] + [Z * 5.01 * F ** (– 0.258700)]
	K–R	1.0 < F < 12.0	12 < BS < 18	LC – [27.3 – 1.1 * (F – 1)] + [0.55 * (18 – BS)] + [Z * (5.01 – 0.1141 * (F – 1))]
	K–R	1.0 < F < 12.0	BS > 18	LC = = [27.3 – 1.1 * (F – 1)] + [0.20 * 08 – BS)] + [Z * (5.01 – 0.1141 * (F – 1))]
Female	S–R	0.1 < F < 1.0	12 < BS < 18	LC = [26.4 * F ** (– 0.156150)] + [0.55 * (18 – BS)] + [Z * 4.85 * F ** (– 0.258700)]
	S–R	0.1 < F < 1.0	BS > 18	LC = [26.4 * F ** (– 0.156150)] + [0.2 * (18 – BS)] + [Z * 4.85 * F ** (– 0.258700)]
	S–R	1.0 < F < 12.0	12 < BS < 18	LC = [26.4 – 1.1 * (F – 1)] + [0.55 * (18 – BS)] + [Z * (4.85 – 0.1104 * (F – 1))]
	S–R	1.0 < F < 12.0	BS > 18	LC = [26.4 – 1.1 * (F – 1)] + [0.2 * (18 – BS)] + [Z * (4.85 – 0.1104 * (F – 1))]

(From Ayoub et al., 1983).

F: frequency of lift
BS: box size (inches)
LC: lifting capacity (pounds)
F–K: floor to knuckle
F–S: floor to shoulder
F–R: floor to reach
K–S: knuckle to shoulder
K–R: knuckle to reach
S–R: shoulder to reach
Z: score of population percentage from normal tables (Z = – 1.6449 for 95%, Z = – 1.2816 for 90%, Z = – 1.0364 for 85%, Z = – 0.6745 for 75%, Z = 0.0 for 50%, Z = 0.6745 to 25%, Z = 1.0364 for 15%, Z – 1.2816 for 10%, and Z – 1.6449 for 5%).

Models are based on the data generated by Snook (1978) and Ayoub et al. (1978a) and are applicable only for the free-style lifting technique.

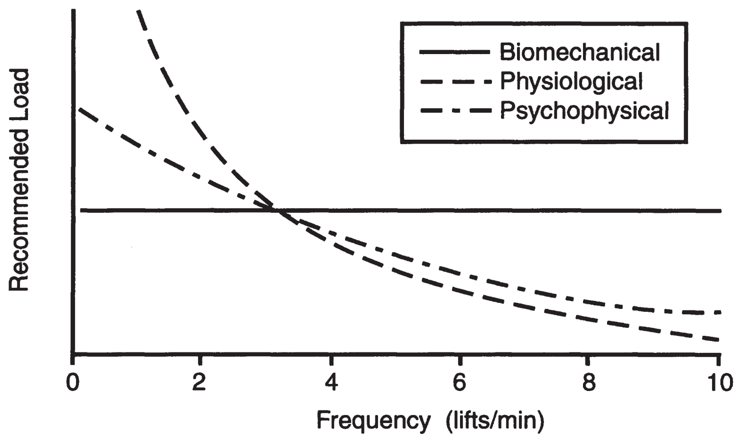

Figure 3. Example of conflict among biomechanical, psychophysical, and physiological criteria (based on Kirn's (1990) models).

THE FUTURE OF MANUAL MATERIALS HANDLING MODELING

As documented in this chapter, previous research to model and understand the adverse effects of manual materials handling tasks on workers has come from three distinctly different approaches. Each has provided insight into the hazards of individual task components that are often encountered in many jobs. Unfortunately, each approach is specifically directed at task components and none of these approaches has proven effective at dealing with jobs in their entirety. At the present time typical manual material handling jobs have a variety of different work components that make it difficult to apply any of the three methods in a pure sense. Workers are often required to lift, carry, hold, and lower loads that vary in location and weight throughout the workday. Typical of this are the many warehousing operations currently done manually in the United States. These jobs have so many different tasks components that it is impractical to analyze each task, and even if this could be done, there is currently no agreed method of aggregating task indices of risk into a job index of risk. Workers are also increasingly being asked to rotate between several different jobs with one of the jobs having a large manual materials handling component. In addition, ten and twelve hour work shifts have become common at many work sites.

The variety of different work tasks being done by typical industrial workers presented a problem for the task oriented models presented in this chapter. Ergonomics practitioners are often confused by conflicting recommendations provided by different models and even by the same model for different tasks performed by a worker within a workday. It is the authors' opinion that future modeling efforts should and will concentrate on providing insight into the musculoskeletal risks of jobs and careers, instead of tasks. Whether this is done by combining the task level approaches documented in this chapter into a composite measure, or through an entirely different method is not entirely clear at this time. However, the greatest need in preventing manual materials handling injuries is understanding the cumulative effects of work tasks done over days, years, and even a work career.

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