CHAPTER 7

ENGINEERING CONTROLS

There are more hazards in manual materials handling than overexertion of the musculoskeletal or cardiovascular systems. Discrete mechanical hazards such as slips, falls and dropping of objects handled with subsequent damage or injury are important - so too are high and low temperature environments which can modify overall bodily response to the exertion of MMH. This chapter reviews these "other" hazards and suggests control methods and design criteria.

Manual materials handling is not a job done in isolation; rather it is part of the overall system by which industry handles and transports materials. Materials handling as a whole represents a large part of industry's costs with an average of 50 tons of materials moved for each ton of product produced. Hence materials handling systems design has emerged as a discipline with its own expertise and procedures. In order to aid the human in his/her role as materials handler it is important to realize the materials handling alternatives available, evaluate the alternatives available and choose the one which is optimum with respect to all criteria. The criteria include performance, cost and maintenance as well as safety. Many of the alternatives to manual materials handling have their own hazards so that this chapter classifies and reviews the methods available to avoid the introduction of substitute hazards into the workplace.

THE MECHANICAL ENVIRONMENT

The chief factors to be considered in designing the mechanical environment are the design of the container itself and the 'couplings' which transmit the container forces through the body to the floor or other working surface. The container itself affects safety directly through its weight and size (biomechanical stresses) and indirectly through the limitations it imposes on methods of holding and carrying it. The human/container coupling affects the ability to exert forces on the object, to maintain grip and to exercise control - all vital to safe handling. The human/work-surface coupling is important for maintaining stability and preventing the initiation of trips, slips and falls.

Container Design

From biomechanical considerations, containers should be as small as possible. In particular every biomechanical model or formula shows that $L5/S_1$ disc pressure is minimized when the center of gravity of the container is as close to the spinal column as possible (e.g., Tichauer, 1971; 1978; Ayoub, et al., 1978) as discussed in Chapter 3. Compactness also allows a load lifted from the floor to move between the worker's legs, decreasing spinal disc pressure.

Any factors which decrease the predictability of the container's response to applied forces will contribute to human error in manual handling. Examples are loads with an unexpected center of gravity (perhaps offset towards one face of the container) or those with a shifting center of gravity. Baffles, dividers or packing should be used to keep the center of gravity in a constant position.

The shape and size of the container are affected by anthropometric dimensions of the work as well as biomechanical considerations. The method of lifting and/or carriage determines the body posture adopted and thus the critical dimensions for safe handling.

For narrow containers one posture adopted is carriage by one hand at the side of the body, as with a suitcase. Containers carried in this way should be as narrow as possible as the maximum acceptable weight is directly related to container width. McConville and Hertzberg (1966) showed that for male military personnel:

$$\text{Maximum Acceptable Weight (kg)} = 35.52 - [0.169 \times \text{Width (cm)}]$$

With weights carried in one hand in this way an equal and opposite torque about the center line of the body is required for lateral balance. This contributes to the spinal stress so that it is usually preferable to carry two lighter containers, one in each hand, for improved balance.

For containers carried at the side of the body the main anthropometric requirement is that the arm can be fully extended downwards so that there are no unnecessary static tensions in the arm muscles. Maximum height to handle center, if the container is to be carried at arm's length, would be 72.5 cm for a 5th percentile (short) male and 65 cm for a 5th percentile female.

For containers carried in front of the body, it is usual to grip the container on each side, either along the base or along the forward edge, and pull the container against the frontal surface of the trunk, thereby supporting part of the weight with body/

container friction (assuming the material is not caustic or hot) thus relieving the static forces in the arm and shoulder muscles. There are no studies on the effect of hand position on this carrying task, and therefore, no recommendations on handle position are possible. It is possible to set limits on container size for this mode of carriage from anthropometric considerations. For the general population, if the forward edge is to be reached the length in the fore- and aft direction should not exceed 71 cm (males) or 65 cm (females). To prevent interference with forward vision, the maximum height of the container above handle position should be 82.5 cm (males) and 80 cm (females). If handles are not placed so that the whole container is above hip height with elbows extended, then interference with the legs will result during walking.

In general, handles should be placed above the container center of gravity for ease of container control but this may not be possible with bulky containers which would then interfere with leg movement. Kellerman and Van Wely (1961) in evaluating different shaped boxes to carry a constant (17.5 kg) weight of flower bulbs found both subjective preference and physiological evidence of the superiority of a wide, shallow container. Their optimum 100 x 30 x 12 cm deep container allowed the worker to carry it at arm's length without interfering with the legs during walking. A compact container is recommended but if deep ones are used it is suggested that handles be above the center of gravity for lifting from floor to table height to reduce stooping, and at or below the center of gravity for carrying or lifting above table height to reduce leg interference.

Human/Container Coupling Design

The handle or hand-hold is the coupling between the container and the worker and should be designed with the worker's hand in mind. The importance of proper hand/container couplings cannot be overstressed. They have a large effect on both the maximum force a worker can exert on a container and on the energy expenditure in manual materials handling tasks. Aside from manual materials handling injuries, Rigby (1973) shows that lack of handles is a prime reason for people dropping products, with resultant product damage. Handle design is usually rather poor in practice. Woodson (1971) notes that off-the-shelf handles appear to be "designed as decorative appointments" rather then "designed to fit the hand". The major problems Woodson reports are insufficient hand clearance, sharp edges which can cut into a worker's hand and too small a handle diameter.

Postures of the hand with respect to grasped objects have been classified by Napier (1956) into

1. A hook grip in which the fingers are flexed around the object and the thumb is not used for gripping.

2. A power grip in which the object is clamped between the partly flexed fingers and palm with the thumb opposing the grip and lying along the plane of the palm, and

3. A precision grip in which the object is pinched between the flexor aspects of the fingers and opposing thumb.

Most handles, hand-holds or gripping aids on containers force the worker to use a hook grip (the least effective) or a power grip. This latter gives a good gripping force and allows a large surface area of hand to be used but it is inefficient if accurate control of the container is needed. Frequently, however, the weight of a container will not allow a precision grip to be used.

The other main consideration in handle design is the nature of the forces that are to be transmitted through the handle to the container. Figure 7.1 shows the forces and torques associated with handle use. Most studies of handle design have assumed that the best size, shape and texture of the handle can generalize from one use to another: their results do not show close enough agreement to support this contention.

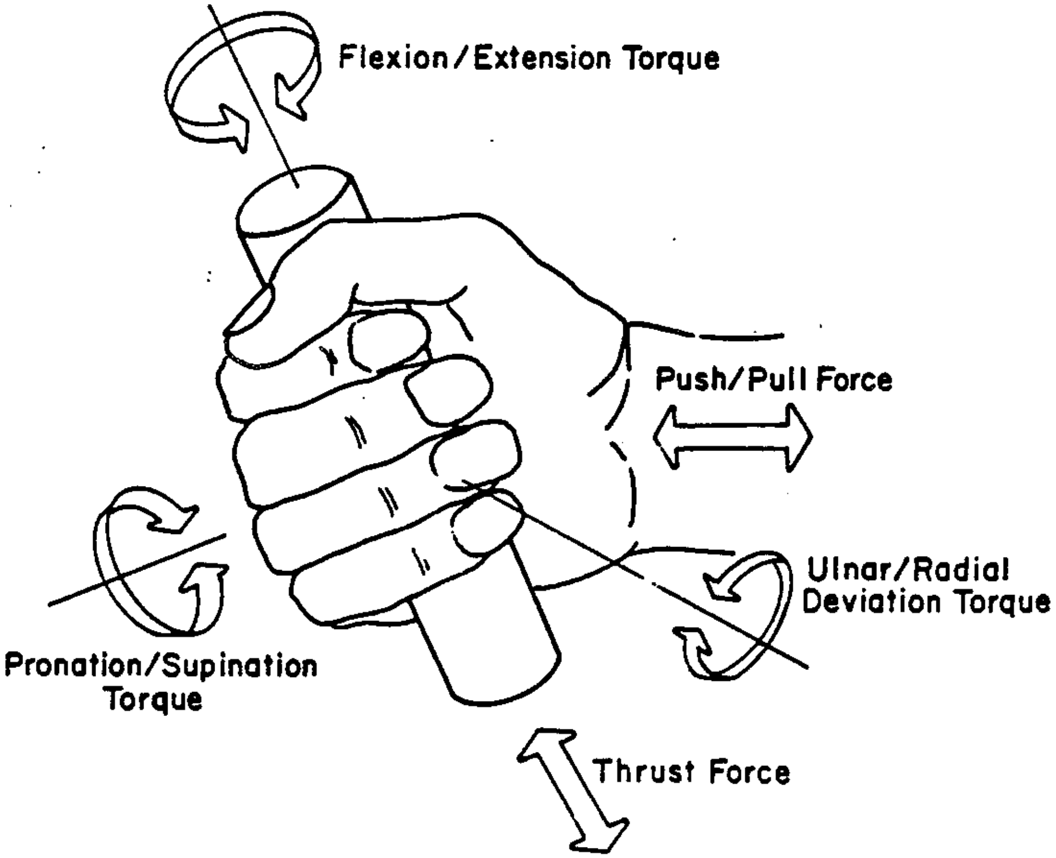


Figure 7.1: Hand Forces and Torques on Handles

One major variable has been handle diameter, whose effect has been measured for different forces and torques and using different criteria. Pheasant and O'Neill (1975) measured flexion/extension torques and found the larger the handle the better, at least up to 70 mm diameter although maximum shear force at the handle surface was greatest for a diameter of 30-50 mm. Thrust forces peaked at about 44 mm diameter. Flexion/extension torque was maximized using rough knurled surfaces in place of smooth cylindrical handles. There was no effect of a wide variety of handle shapes on maximum torques when the effect of diameter was eliminated.

The pronation/supination torque was measured as a function of handle diameter by Saran (1973), who found that a 2.5 cm diameter handle was preferred over either a 1.9 or a 3.2 cm handle. There were no differences between handle diameters in terms of electromyographic (EMG) activity of the muscle groups involved in the task.

Tasks requiring the production of a push/pull force have been used to evaluate handle diameter in a number of studies. This is perhaps the most relevant type of task for designing container handles. Ayoub and LoPresti (1971) found a relatively flat optimum between about 25 mm and 64 mm diameter when EMG was measured. However grip forces were optimum for a diameter of 38 mm. Khalil (1973) measured EMG activity for three diameters of cylindrical handle, (3.5, 5 and 7 cm) plus an elliptical handle 5 cm long x 3.2 cm wide and a 5 cm diameter sphere. Of all these handles the 3.2 cm diameter handle was best.

Two unpublished studies both requiring a pull force (Sanderson, 1976; Salvaterra and Chiusano, 1977) have tested cylindrical handles in different tasks. The former used a holding task and handles from 1 to 2.5 cm and found an optimum at 1.9 cm. The latter used both a subjective scale and a change in grip strength following a one minute holding of a 15 kg container to evaluate handles from 1 to 5 cm. Optima were found in each case at the center of the range, 1.9 cm and 3.8 cm respectively.

Other recommendations can be made based on different criteria. If the hand is to fit the handle with no overlap of fingers and thumb then Garret's (1971) anthropometric data would suggest 41 mm as a maximum diameter for a 5th percentile male without gloves. Similarly, guidebook recommendations in human engineering recommend diameters as follows (Rigby, 1973):

Weight of Item	Miminum Diameter
15 lb.	6 mm
15-20 lb.	13 mm
20-40 lb.	19 mm
40 lb.	25 mm

These values are quoted without evidence as to their efficacy.

Design Recommendations for Handles

For final recommendations on handle diameter, there is little agreement in the literature, although diameters from 25 to 38 mm receive more support than most and thus must, reluctantly, be recommended. The elimination of sharp edges, seams, ribbing, and corners appears to be an equally important criteria. The handle should be textured to provide maximum gripping force, particularly if other than a pull force is to be exerted. The shape of the handle is better cylindrical than molded to the contours of the hand. Tichauer (1966, 1971, 1978) demonstrates the limitations of such form-fitting handles. It is almost impossible to design finger grooves into a handle in such a way that they fit a large percentage of the population. Thus any set of finger grooves will impair performance for those workers not perfectly fitted.

Handle or hand-hold width should be at least 11.5 cm, with 5 cm clearance all around the handle to accommodate a 95th percentile hand. If use with gloves is anticipated, at least 2.5 cm should be added to these dimensions.

Worker/Floor Surface Coupling

The worker/working surface coupling has been cited as a causative factor in a large percentage of accidents, particularly trips and falls (Safety Science, 1977). The major types of accidents of this type are:

1. slip (loss of traction on work surface)
2. trip (movement of lower body arrested)
3. mis-step (putting foot down where there is no support)

These accident patterns account for almost three quarters of work-surface related accidents. The major mediating variable in this type of accident is the coefficient of friction between the shoe sole and the working surface. Pfauth and Miller (1976) review shoe/working surface friction and find it affected by:

1. work surface material (wood, concrete, steel, tile, etc.; Irvine, 1967; Kroemer, 1971, 1974; Sigler, 1943).
2. surface coating (e.g., waxes can both increase and decrease friction; Braun and Roemer, 1974).
3. floor condition (clean or dirty; wet, dry or greasy; e.g., Irvine, 1967; Kroemer, 1971, 1974; Sigler, 1943).

4. floor angle (Harper, Warlow & Clark, 1961; found higher coefficients of friction were needed on increasingly steeper slopes).

5. shoe sole/heel composition and contact area (rubber soles and certain synthetic soles are better than leather under dry conditions, but differences reduce or even reverse under wet conditions; Irvine, 1967; Kroemer, 1971, 1974; Sigler, 1943; Safety Sciences, 1977).

6. The style of shoe (Harper, Warlow & Clarke, 1961, found that shoes with high or narrow heels are the most hazardous). In a related area Tichauer (1966) found potential problems of biomechanical stresses from lifting in higher heels.

The general recommendation is to adjust shoes and working surfaces to give a coefficient of static friction of at least 0.4 and preferably 0.5. Unnoticed changes in surface friction are implicated in many accidents. Going from a less slippery floor to a more slippery one produces slips, the opposite change produces trips and mis-steps. These unnoticed changes can be reduced by:

1. ensuring that different surface materials or coatings have transition zones between them.

2. clearly marking any surface friction change.

3. using good housekeeping procedures to reduce transient changes in surface friction such as spills, worn spots, loose or irregular floors.

These recommendations are of particular importance in manual materials handling where any handling other than direct lifting involves horizontal inertial forces transmitted from the container to the body. Such forces require increased frictional forces to prevent foot slippage. The carriage of weights also affects the body's learned reflexes for recovering from a slip or trip both by changing the normal weight distribution of the body and by preventing the arms from being used to regain balance or recover from the fall. Finally, if a fall does occur, the container becomes another moving mass in close proximity to the falling operator, with potential for both crushing and puncturing the body.

THE VISUAL ENVIRONMENT

While manual materials handling operations rarely demand the fine visual discrimination of delicate assembly work, they do require control of the visual environment for optimum performance and safety.

The total amount of light needed is easier to specify than the type of light. The task of manual materials handling involves vision of the container, the workplace around the container and the surface on which the operator stands. Following the IES Code for Interior Lighting, an illuminance of 150 lux in each of these areas is a recommended minimum.

Type of lighting can have a large effect on visual performance, particularly in the areas of depth perception and surface texture perception. The aim in both of these areas is to provide sufficient visual contrast for safe operation. Contrast, which depends on the difference in light reflected from two surfaces, can be controlled either by differential illumination or by differing reflectance. Differential illumination should apply to stairs or changes in walking surface such as shoe/surface friction changes. Low, angled illumination is recommended for enhancing surface texture to warn operators of changes in shoe/surface friction. Depth perception errors are usually controlled by changing the reflectance of the container and task to provide additional contrast. Color contrast can also be used in critical areas such as edges of steps, loading docks and ramps where the consequences of misperception are severe.

The American National Standard Z53.1, 1967, Safety Color Code recommends the Yellow be used for marking hazards that may result in accidents from slipping, falling, striking, etc. Yellow indicates flammable liquid storage cabinets, materials handling equipment, radiation hazard areas, etc. Often black stripes or a checkerboard pattern can be used with the yellow color.

In situations where the operator may be unfamiliar with a particular container, or where a variety of containers are handled, appropriate labels and markings should be put on the container. These should be designed to ensure that the best handling position is adopted and that the appropriate force is applied. All lettering should be of a uniform style (e.g., MIL STD 33558).

Labelling should indicate handhold positions, cautions against single person lifting if the load is heavy, or a note of caution if its center of gravity is not near the center of the container, or if its center of gravity is likely to shift. The center of gravity and total weight warnings are particularly important with modern packaging methods, where the size of the container may bear very little relationship to its weight and dynamic characteristics.

Labels should be printed on all sides of a container, facing in at least two directions so that they are visible to the operator at all times. Labelling should aim for brevity and simplicity if it is to be used and understood on the maximum number of occasions.

THE THERMAL ENVIRONMENT

Early studies on mine workers showed a relationship between environmental (air) temperature and accident rates (Vernon and Rusher, 1920)

A number of studies (Edholm, 1967) have confirmed increased accident rates away from the comfort zone (18°C to 21°C, 65°F to 70°F) and a greater effect of temperature for older workers. It is thus particularly important to ensure that thermal stress does not contribute to manual materials handling safety problems.

Cold environments are not usually a problem in MMH safety; the strenuous nature of many of the MMH jobs gives a rate of metabolic heat production sufficient to prevent hypothermia. However, colder environments can lead to reduced dexterity (e.g., Wentzel, 1968) which could increase human error in MMH. Also colder temperatures can motivate workers to wear protective clothing, particularly at the extremities. Powell, et al., (1971) found decreased accidents at lower environmental temperatures in a warehousing operation, much of the effect due to the operators wearing their safety gloves in colder weather for reasons of thermal comfort.

In hot environments the added metabolic heat produced inside the body by MMH work can result in greater risk of overstrain and heat illnesses. To prevent excessive exposure to heat, an assessment must first be made of whether or not a heat problem exists. Currently, the most accepted method for determining heat load is decribed in the Threshold Limit Value (TLV) booklet of the American Conference of Governmental Industrial Hygienists (ACGIH, 1980). Figure 7.2 shows the lines of permissible exposure to work in hot environments as developed by Dukes-Dobos and Henschel (Dukes-Dobos, 1976) which was adopted by the ACGIH as the TLV for heat stress. The values given apply to acclimated workers who are physically fit.

Various measures are possible for the alleviation of the heat stress problem. All seek to reduce heat storage by the body, either by limiting input heat load from the environment, by limiting metabolic heat generation, or by limiting exposure duration. In practice this can mean air conditioning, radiant heat shielding, forced air movement, clothing design to minimize heat absorption and maximize evaporative cooling, and finally the design of work-rest schedules to prevent body temperature from increasing during the work shift.

Other methods of estimating metabolic costs for manual materials handling tasks are available (Givoni and Goldman, 1971; Garg, et al., 1978).

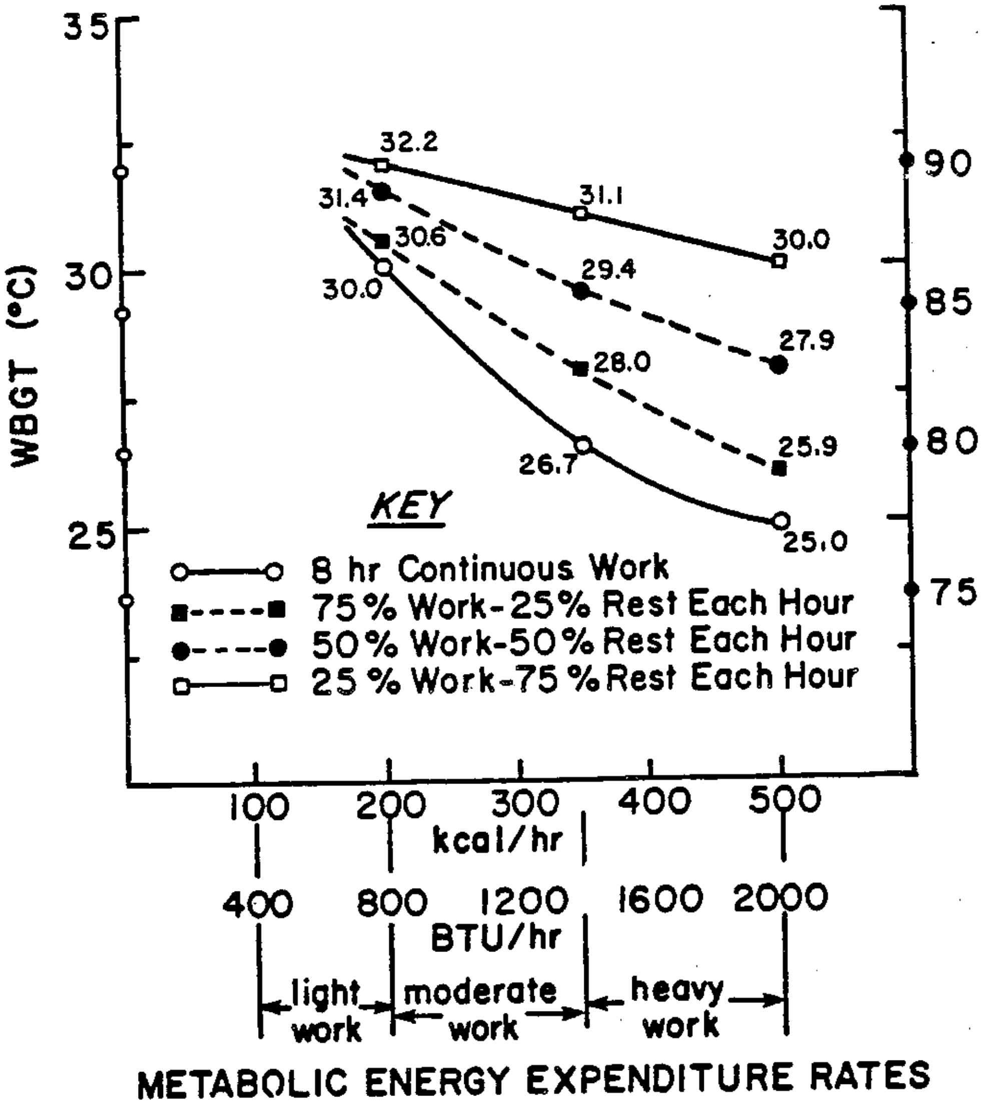


Figure 7.2: Lines of Permissible Exposure to Work in Hot Environments (Dukes-Dobos, 1976)

These can be combined with detailed treatments of the physics of heat transfer between human beings and their working environment (Berenson and Robertson, 1973) so that a detailed analysis of human thermal load can be made (Givoni and Goldman, 1971, 1973). These allow the effects of changes in environment, clothing and workload to be predicted and engineering controls to be installed in advance.

MATERIALS HANDLING SYSTEM ALTERNATIVES

The materials handling function is ubiquitous throughout industry occurring in at least seven areas.

1. Transportation of Raw Materials. Each delivery of materials to the plant whether by road, air, rail or water requires material moving equipment and people. Often such transportation of raw material is performed by outside carriers over which the plant management has little control. Still, their interaction with the manufacturing process must be recognized as important.

2. Receiving. Unloading the material from the transporting vehicle and moving the materials to their assigned places constitutes materials handling. Furthermore, inspection for weight, quality, quantity, etc., generally involves handling operations. Often, the handling itself takes more time than the inspection or storing action.

3. In-process Handling. The handling of material within the plant and particularly between work stations constitutes major materials handling problems with respect to effort, cost, and danger of accidents. Pieces may be moved many times in manufacturing plants either as single elements or combined with others in subsystems or units. Storage of in-process parts between operations is a very critical area of materials handling.

4. Handling at the Work Place. This is one of the most overlooked but costly operations in materials handling. It usually involves manual movement of material among fixtures and jigs, into and from machines, and the disposal of by-products and wastes. This is a phase in materials handling which contributes significantly to injuries and accidents.

5. Handling of Wastes and By-products. Rejects, wastes and by-products produced in the manufacturing process, or used packaging material, must be moved and disposed. This may involve sorting of materials that can be used again or recycled, and of those materials that are discarded. This is also an often overlooked aspect of materials handling.

6. Warehousing. The storing, stocking, order picking, assembly of orders, packing and movement out of the warehouse are material handling operations.

7. Distribution. The transportation of the finished or processed goods and materials is the last part of materials handling in the manufacturing cycle. This usually involves, like the transportation of raw materials, road, rail, air or water vehicles, and is often done by outside carriers.

Materials handling systems can be classified in many ways by their function and purpose. The International Material Management Society and the ASME have adopted a decimal classification system with nine major classes. The four most useful classes within a factory are:

1.000 Conveyors
2.000 Cranes and hoists
3.000 Positioning equipment
and 4.00 Industrial vehicles

Positioning equipment is used to transfer material from workplace to materials handling equipment or vice versa. It includes manipulators, dumpers, up-enders, positioning tables, lifts, jacks and transfer machines. As such positioning equipment provides an alternative to the unaided human operator at the workstation itself where many manual materials handling problems occur.

At the workplace simple job aids can often facilitate materials handling tasks. Examples are:

1. Hooks. The worker should be trained in the use of hand or packing hooks so that they will not glance off hard objects. If the hook is carried in the belt, the point must be covered.

2. Bars. The major hazard in the use of a crow bar is that it may slip. The point or edge should have a good "bite".

3. Rollers. Rollers are often used to move heavy and bulky objects. The principal hazard is that fingers or toes may be pinched or crushed between a roller and the floor.

4. Jacks. All jacks should be marked to indicate the safe load they can support. The surface onto which a jack is placed must be level and clean and be sturdy enough to support the load. After the load is raised, substantial horses or blocking should be placed under it for support. Workmen using jacks should wear safety shoes and instep guard protection because handles may slip, or parts may fall.

5. Platforms. Platforms are useful for loading and unloading, provided that the load is maintained at a convenient height for lifting and handling.

6. Trestles. These and other supports may be used for maneuvering long loads on the point of balance, or for readjusting the grip or carrying posture.

The other three types of materials handling equipment are used essentially between workstations. Their characteristics, functions and uses have been well summarized by Apple (1971) as follows.

Conveyors

These gravity or power devices are commonly used for moving uniform loads continuously from point to point over fixed paths where the primary function is movement.

1. Common examples include:
   - a. roller conveyors,
   - b. belt conveyors,
   - c. screw conveyors,
   - d. chutes,
   - e. monorails, and
   - f. trolley conveyors.
2. Conveyors are generally useful when:
   - a. loads are uniform,
   - b. materials move continuously,
   - c. routes do not vary,
   - d. loads are constant,
   - e. movement rate is relatively fixed,
   - f. conveyors can bypass cross traffic,
   - g. the path to be followed is fixed, and
   - h. movement is from one point to another.

Cranes and Hoists

These overhead devices are usually utilized to move varying loads intermittently between points within an area fixed by the supporting and guiding rails, where the primary function is transferring.

1. Common examples include:
   - a. overhead traveling cranes,
   - b. gantry cranes,
   - c. jib cranes,
   - d. hoists, and
   - e. stacker cranes.
2. Cranes and hoists are most commonly used when:
   - a. movement is within a fixed area,
   - b. moves are intermittent,
   - c. loads vary in size and weight,
   - d. cross traffic will interfere with conveyors, and
   - e. loads handled are not uniform.

Industrial Trucks

These hand or powered vehicles (nonhighway) are used for movement of mixed or uniform loads intermittently over varying paths which have suitable running surfaces and clearances and where the primary function is maneuvering or transporting.

1. Common examples include:

   a. forklift trucks,
   b. platform trucks,
   c. two-wheel hand trucks,
   d. tractor-trailer trains, and
   e. hand stackers.

2. Industrial trucks are generally used when:

   a. materials are moved intermittently,
   b. movement is over varying routes,
   c. loads are uniform or mixed in size and weight,
   d. cross traffic would prohibit conveyors,
   e. clearances and running surfaces are adequate and suitable,
   f. most of the operation consists of handling - lifting, maneuvering, stacking, and the like, and
   g. material can be put into unit loads.

Other classficatory schemes are possible, for example by the power requirements. At least three classes can be distinguished: Human Powered, Gravity Powered and Self-Powered. The total energy expended by the human operator is obviously highest for human powered systems with consequent increased probability of overstrain. But the total energy marshalled, and hence available for damage and injury, is greater for gravity- and self-powered systems.

The final classificatory variable is the coupling between the load and the materials handling system. Special-purpose attachments are available in profusion; forks, clamps, hooks, platforms and hoppers are all used across the other classifications of materials handling systems.

The aim in this classification is to enable the materials handling system designer to specify the function of the equipment rather than the equipment itself. This ensures that novel approaches to materials handling problems are not overlooked because of overfamiliarity with particular solutions.

POTENTIAL SAFETY AND ERGONOMIC PROBLEMS

Each of the major classes or materials handling equipment has problems of human/machine mismatch which are potential and actual sources of accident causing errors.

Conveyors

The major problem with conveyors, aside from purely mechanical entrapments, is that work is externally-paced. Human performance is inherently variable with successive cycle times on a repetitive task having a standard deviation of 10-20% of the mean time. Any attempt at external pacing of the operator gives rise to time-stress induced errors, even when the operator is paced at well below his/her mean unpaced performance. Murrell (1969) found that if missed components (errors) could only be tolerated at 0.5% of total production, then production rates had to be set 20-30% below optimum conveyor speed.

Not only must conveyor based systems be designed taking account cycle-to-cycle variability of one operator, but their operation must allow for operators of different abilities at each workstation. With typical between-operator ranges of 2:1 in cycle times this means that large numbers of operators will either be over-stressed or under-stressed in their work. One solution, as Sury (1965) shows is to increase the tolerance of the conveyor system for fast and slow cycles. He found that a time tolerance of 99% of the cycle time distribution for each operator was needed to remove the effects of too-rigid pacing. Buffer stocks between stations achieve the same effect.

Conveyors and their associated pacing have infamous effects on employee attitudes. For example Coetsier (1965) found that the imposition of pace was a more significant factor in negative attitudes than was the actual rate of work. Davies (1965) cites the use of a conveyor to enforce a particular work output as replacing the management functions of managers.

However, not all conveyors are paced. Many gravity or powered and free conveyors merely transport goods between workstations where the goods form a waiting line until operated upon by the worker. Another positive use of conveyors is the use of mobile conveyors or rollers to facilitate loading and unloading of trucks and containers.

Cranes and Hoists

Considering the dangers involved when heavy loads are suspended, cranes are among the most dangerous pieces of material handling equipment. For this reason, specific requirements must be met by all cranes. Overhead and gantry cranes must meet the design specifications of American National Standard B 30.2.0 (OSHA regulation 1910.179); all crawler, locomotive and truck cranes must meet the design specifications of American National Standard B301.5 (OSHA regulation 1910.180). Cranes installed before August 27, 1971, must be modified to conform to these requirements (see National Safety Council, Supervisor's Safety Manual).

1. The crane cab, and all controls, must be designed for good visibility, and safe operation. Sell (1977) showed how an integrated cab for an overhead crane could be designed.

2. Of course, no crane should be loaded beyond its rated load capacity, the load including the weight of all auxiliary handling devices such as hoist blocks, hooks, and slings.

3. Load hooks, chains, ropes, and the hoisting device itself must be clearly marked with the maximum allowable load.

4. Loads must not be carried over people, and may not be moved while a person is on the load or hook.

5. The operator must be thoroughly trained. He must not leave his position at the controls while the load is suspended.

6. Standard signals should be used between the crane operator and the signal man on the ground.

Most of the materials handling accidents investigated by Coleman, et al., (1978) were connected with falling, slipping, or bumping of the load. The major factors in such accidents were inadequate communications between the crane operator, the hitcher, and the signal man. Often the visibility from the cab was insufficient, the controls inadequate, and the overall design required tiring body positions. Simple ergonomics principles of control positions and directions of movement, workplace layout and visibility are readily available (e.g., McCormick, 1976; VanCott and Kinkade, 1972) and should be used in design or redesign.

Hoists and particularly air-balance hoists are useful at the workplace where heavy components can be moved with only small (control) forces having to be supplied by the human operator.

Industrial Trucks

Human factors and safety design weaknesses found by Coleman, et al., (1978) concerned missing or inadequate safety devices, lack of standardization in braking, reduced visibility, cramped driver compartments, seats not damping transmission of road impacts and vibrations, and not providing sufficient body support.

Hazards often encountered in the operation of powered and hand trucks include:

1. contact with the moving parts of the truck,
2. falling of the load, particularly at corners and on inclines,

3. rollover,
4. collision between the truck and other object,
5. the operator getting pinned between the truck and another object, and
6. the truck running up the heels of the walking operator.

Many of these hazards also apply to dollies and wheelbarrows. They can be reduced or eliminated by using the following guidelines.

1. All exposed handles should be equipped with knuckle guards so that the operator's hands cannot be jammed against external obstructions.

2. All wheels should be recessed or otherwise guarded.

3. All trucks should have brakes that apply automatically when the handle is either fully raised or fully lowered, or released.

4. Major features should be standardized, e.g., brake activation on powered trucks.

Fox (1971) found many instances of negative transfer between different vehicles with different positions and directions of controls. He also found critical incidents caused by errors in blind reaching for controls while the driver's vision was directed to the load rather than the controls.

5. All operators must be trained to follow safe practices, such as
   a. proper loading (i.e., so that the vehicle is balanced, that the load will not fall off, that vision is not obscured, etc.)
   b. leaving the truck facing the traffic
   c. maintaining safe speed
   d. backing loads down inclines to avoid front end tipping
   e. lowering the fork to floor level when not in use
   f. chocking wheels if parked on an incline.

Pertaining OSHA regulations are detailed under Part 1910, Subpart N. particularly section 1910.178. Two anonymous articles, "powered Hand Trucks," (July 1975 issue, National Safety News, 53-57), and "Industrial Trucks - Their Operations and Maintenance," (September 1975 issue, Industrial Engineering, 32-37) discuss many of the safety features and lists applicable safety standards and recommendations.

Fork-lift trucks have the dubious distinction of violating many human engineering principles and recommendations, and of having many accidents. Human engineering data and recommendations shoudl be made as the basis for design or purchase of a new fork-lift truck. In its operation, many mishaps can be avoided by using "safe practices" in training the new operator, in monitoring the operator's performance, and by enforcing safe practices by positive (reward) and negative (punitive) control measures (Lovested, 1977).

Again many of these problems can be alleviated by the intelligent application of ergonomics/human factors principles. The environment in which the industrial truck operates can have a large effect on its efficiency and safety. Drury and Dawson (1974) evaluated control performance of five powered fork trucks and found that considerable lateral room was required even to drive them consistently in a straight line. For drivers concentrating totally on vehicle control, an aisle width of 0.5 m greater than truck or load width was required. In more realistic situations where the operator must monitor the load stability, plan his/her course through a factory and be alert to avoid other traffic much greater clearances are needed.

For human powered vehicles, Drury, Barnes and Daniels (1975) found that large wheels gave easier handling and that, again, adequate clear aisle widths had to be provided. Handles should be about 1 meter above the floor for maximum force exertion. With any human powered vehicle flatness of floors is essential and special care must be taken to avoid sudden floor steps of even a few millimeters as they can cause large increases in the force necessary to push or pull the vehicle.

CHAPTER 8

RECOMMENDATIONS

This chapter outlines load limit recommendations for lifting tasks. Sections on how to identify a hazardous lifting job, how to interpret the guidelines and how to apply them to actual lifting situations are provided. In addition, brief summaries of Chapter 6, Administrative Controls and Chapter 7, Engineering Controls, are included.

It is intended that this chapter will provide the Industrial or Safety Engineer with an easy means to quickly scan the Guide, pick out important points and apply them to the appropriate situation. References to earlier chapters are made if a more thorough and detailed discussion of a topic is desired.

DEFINITION OF A LIFTING TASK

For the purpose of this Guide, a lifting task is considered to be the act of manually grasping and raising an object of definable size without mechanical aids (i.e., hoists, conveyors, block and tackle, etc.). The time duration of such an act is normally less than two seconds, and thus little sustained exertion is required (as opposed to holding or carrying activities). The lifting limits presented in this chapter do not apply to all kinds of lifts. They are intended to apply only for:

a. smooth lifting
b. two-handed, symmetric lifting in the saggital plane (directly in front of the body; no twisting during lift)
c. moderate width, e.g., 75 cm (30 in) or less
d. unrestricted lifting posture
e. good couplings (handles, shoes, floor surface)
f. favorable ambient environments.

It is assumed that other manual handling activities such as holding, carrying, pushing, pulling, etc., are minimal. When not engaged in lifting activities, the individual is assumed at rest. The assumed work force is physically fit and accustomed to physical labor.

The Guide does not include "safety factors" commonly used by engineers to assure that unpredicted conditions are accommodated.

LIFTING TASK VARIABLES

The primary task variables identified earlier in this Guide on the basis of epidemiology (Chapter 2), biomechanics (Chapter 3), physiology (Chapter 4) and psychophysics (Chapter 5) of lifting include:

1. Object weight (L) - measured in kilograms (pounds)
2. Horizontal location (H) - of the hands at origin of lift measured forward of the body centerline or midpoint between ankles (in centimeters or inches)
3. Vertical location (V) - of the hands at origin of lift measured from floor level in centimeters (inches)
4. Vertical travel distance (D) - from origin to destination of lift in centimeters (inches)
5. Frequency of lifting (F) - average number of lifts per minute
6. Duration or period - assumed to be occasional (less than one hour) or continuous (8 hours)

The latter two variables (lift frequency and period) are the most difficult to define and consequently measure and provide guidance. For the purpose of this Guide jobs will be grossly classified in three categories:

1. Infrequent - either occasional or continuous lifting less than once per 3 minutes
2. Occasional high frequency - lifting one or more times per 3 minutes for a period up to 1 hour
3. Continuous high frequency - lifting one or more times per 3 minutes continuously for 8 hours.

5

Evidence presented in earlier chapters shows that for infrequent lifting a person's musculoskeletal strength (Chapter 5) and potential high stress to the back (Chapter 3) are the primary limitations to ability. As such, biomechanical variables are predominant in determining hazard. Occasional high frequency lifting results in psychophysical stress (Chapter 5) and possible muscle fatigue as the primary limitations. For continuous, high frequency lifting the primary limitations are based on cardiovascular capacity and metabolic endurance (Chapter 4).

Table 8.1 summarizes which task variables are emphasized by the four approaches examined in Chapters 2-5. A careful review of these approaches shows two important points. First, all of the task variables are highly interactive. In other words, the

Table 8.1: Emphasis on task variables by alternative approaches.

	Epidemiology (Ch. 2)	Biomechanics (Ch. 3)	Physiology (Ch. 4)	Psychophysics (Ch. 5)
Object Weight (L)	X	X	X	X
Horizontal Location (H)	X	X	X	X
Vertical Location (V)	X	X	X	X
Travel Distance (D)			X	X
Frequency of Lift (F)	X		X	X
Duration or Period (P)			X	

importance of object weight (for example) is highly dependent on where the weight is located (horizontally and vertically), how far it must be moved, and how frequently. Thus, none of these variables should be evaluated independently.

Secondly, the four approaches taken separately may lead to different conclusions. For example, metabolic criteria (Chapter 4) can lead one to believe lifting heavy loads infrequently is preferred to frequent lifting of lesser loads (due to the cost of moving the body). From a biomechanical or strength point of view, (Chapters 3, 5) object weight should be minimized regardless of frequency.

Another example has to do with object location. A person is generally strongest when lifting with the legs and back. Were strength the only criterion, (Chapter 5) one would favor leaving objects on the floor rather than on shelves. Of course, biomechanical low back compression (Chapter 3) and cardiovascular (Chapter 4) criteria would deem this least desirable.

CRITERIA FOR GUIDELINE

It is concluded, regardless of the approach taken to evaluate the physical stresses of lifting, that a large individual variability in risk of injury and lifting performance capability exists in the population today. This realization requires that the resulting controls be of both an engineering and administrative nature. In other words, there are some lifting situations which are so hazardous that only a few people could be expected to be capable of safely performing them. These conditions need to be modified to reduce stresses through job redesign. On the other hand, some lifting conditions may be safely tolerated by some people, but others, particularly weaker individuals, must be protected by an aggressive selection and training program. To specifically define these conditions two limits are provided based on epidemiological, biomechanical, physiological, and psychophysical criteria.

1. Maximum Permissible Limit (MPL)

   This limit is defined to best meet the four criteria:

   a. Musculoskeletal injury rates and severity rates have been shown to increase significantly in populations when work is performed above the MPL.

   b. Biomechanical compression forces on the L_5/S_1 disc are not tolerable over 650 kg (1430 lb) in most workers. This would result from conditions above the MPL.

   c. Metabolic rates would exceed 5.0 Kcal/minute for most individuals working above the MPL.

   d. Only about 25% of men and less than 1% of women workers have the muscle strengths to be capable of performing work above the MPL.

2. Action Limit (AL)

   The large variability in capacities between individuals in the population indicates the need for administrative controls when conditions exceed this limit based on:

   a. Musculoskeletal injury incidence and severity rates increase moderately in populations exposed to lifting conditions described by the AL.

b. A 350 kg (770 lb) compression force on the L_5/S_1 disc can be tolerated by most young, healthy workers. Such forces would be created by conditions described by the AL.

c. Metabolic rates would exceed 3.5 for most individuals working above the AL.

d. Over 75% of women and over 99% of men could lift loads described by the AL.

Thus, properly analyzed lifting tasks may be of 3 types:

1. those <u>above the MPL</u> should be viewed as unacceptable and require engineering controls
2. those <u>between the AL and MPL</u> are unacceptable without administrative or engineering controls
3. those <u>below the AL</u> are believed to represent nominal risk to most industrial workforces.

To illustrate this point, Figure 8.1 shows the three regions and boundaries defined for infrequent lifting ($F < .2$) from the floor ($V = 15$ cm [6 in]) to knuckle height ($D = 60$ cm [24 in]). Depending on the size of the object, in terms of horizontal hand location, the maximum weight which can be lifted can be determined

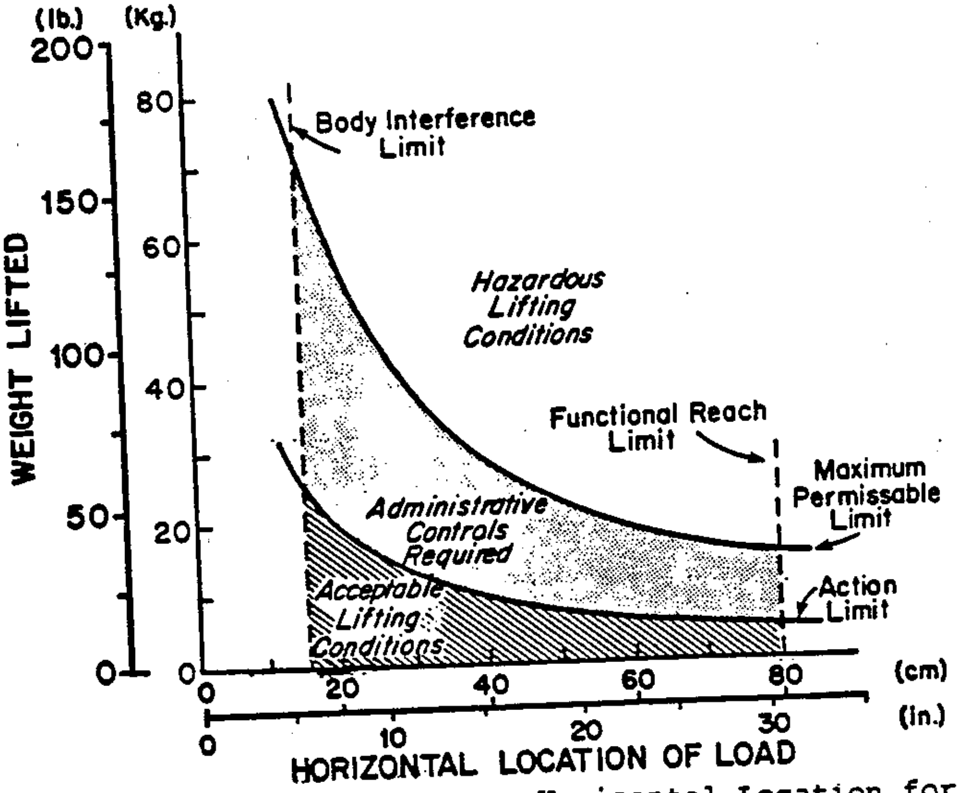


Figure 8.1: Maximum Weight versus Horizontal Location for Infrequent Lifts from Floor to Knuckle Height

GUIDELINE LIMITS

With the large number of task variables (5 in this case) which modify risk during lifting it is virtually impossible to provide a simple yet accurate procedure for evaluating all possible jobs. This problem is further complicated by the need to satisfy four separate criteria (epidemiological, biomechanical, physiological, and psychophysical). The following guideline is the simplest form known which best satisfies the four criteria.

In algebraic form:

$$\text{AL (Kg)} = 40(15/H)(1-.004|V-75|)(.7+7.5/D)(1-F/F_{max}) \text{-metric units}$$

or

$$\text{AL (lb)} = 90(6/H)(1-.01|V-30|)(.7+3/D)(1-F/F_{max}) \text{-U.S. Customary units}$$

$$\text{MPL} = 3\ (\text{AL})$$

where H = horizontal location (centimeters or inches) forward of midpoint between ankles at origin of lift

V = vertical location (centimeters or inches) at origin of lift

D = vertical travel distance (centimeters or inches) between origin and destination of lift

F = average frequency of lift (lifts/minute)

F_{max} = maximum frequency which can be sustained (see Table 8.2)

For purposes of this Guide, these variables are assumed to have the following limits.

1. H is between 15 cm (6 in) and 80 cm (32 in). Objects cannot, in general, be closer than 15 cm (6 in) without interference with the body. Objects further than 80 cm (32 in) cannot be reached by many people.

2. V is assumed between 0 cm and 175 cm (70 in) representing the range of vertical reach for most people.

3. D is assumed between 25 cm (10 in) and (200-V) cm [(80-V) in]. For travel less than 25 cm, set D = 25.

4. F is assumed between .2 (one lift every 5 minutes) and F_{max} (see Table 8.2). For lifting less frequently than once per 5 minutes, set F = 0.

Table 8.2: F_{max} Table.

AVERAGE VERTICAL LOCATION (cm)(in)

PERIOD	$V > 75$ (30) Standing	$V \le 75$ (30) Stooped
1 hour	18	15
8 hours	15	12

The above equations for the action limit (AL) and maximum permissable limit (MPL) represent a multiplicative factor weighting for each task variable. The first factor

$$\text{H Factor} = (15/H)$$

represents the importance of the horizontal location (H). If H = 15 cm this factor is 1 and no adjustment for horizontal location is necessary. If H = 75 cm, this factor is 15/75 = .20 meaning the AL is reduced from 40 to 40(.20) = 8 kg.

The factor for vertical location involves the absolute deviation of V from 75 cm (approximate knuckle height). For V = 75, the V factor is

$$\begin{aligned}\text{V Factor} &= (1-.004|V-75|)\\ &= (1-.004(0)) = 1\end{aligned}$$

For V = 15,

$$\begin{aligned}\text{V Factor} &= (1-.004|15-75|)\\ &= 1-.004(60) = .76\end{aligned}$$

Likewise for V = 135,

$$\begin{aligned}\text{V Factor} &= (1-.004|135-75|)\\ &= 1-.004(60) = .76\end{aligned}$$

Likewise, the D factor ranges from 1 to .74 as D varies from 0 to 200 cm.

$$D \text{ Factor} - (.7+7.5/D)$$

For D = 0 set D = 25 (the minimum allowed value), then

$$D \text{ Factor} = (.7+7.5/25) = 1.0$$

For D = 200,

$$D \text{ Factor} = (.7+7.5/200) = .74$$

The F factor is a bit more complicated. If the lifting originates below 75 centimeters (on the average $V \leq 75$) and is performed continuously throughout the day, $F_{max} = 12$ (as given in Table 8.2). If the observed frequency is 6 lifts per minute (F = 6) then,

$$F \text{ Factor} = (1-F/F_{max})$$
$$= 1-6/12 = .5$$

The effective weight which can be lifted is thus halved due to frequency of lifting required.

Combining factors is illustrated for continuous lifting below knuckle height with average H = 20 cm, V = 40 cm, an average distance of D = 100 cm, at a rate of 6 lifts per minute; then

$$AL = 40 \ (15/20)(1-.004|40-75|)(.7+7.5/100)(1-6/12)$$
$$= 40 \ (.75)(.86)(.78)(.5) = 10 \text{ kg.}$$

$$MPL = 30 \text{ kg.}$$

The mechanics of this example would be exactly the same using the U.S. Customary form of the equation and the task variable limits given on page 120. The weight handled on the job could be compared directly with these values. Suppose the load was 35 kg (above the MPL). In this case, one "engineering control" might be to reduce the frequency of lifting from 6 per minute to 1 per minute (admittedly a drastic change). This would increase the frequency factor from .5 to .92 and consequently the

$$AL = 18.4, \text{ and}$$

$$MPL = 55.2$$

Viewing the relative weights of each factor (.75)(.86)(.75)(.50) in this case allows a quick evaluation of the relative weights associated with changes in any factor. Frequency of lifting is the biggest discounting factor (.5) in this case and should receive first consideration.

Reducing frequency to 1 lift per minute would lower the stressfulness of the job to within the "administrative controls" region. In this case, 35 kg is between AL = 18.4 and MPL = 55.2. This should not preclude further "engineering controls". It is important to realize that the job still cannot be safely performed by most women or the majority of men. Further reductions in the frequency (factor = .92) would be ineffective since this factor can only increase to 1.0. The load probably cannot be brought appreciably closer to the body (H = 15 versus H = 20 cm).

The best engineering solution at this point would be to change the load weight. Halving the weight (from 35 kg to 18 kg) would be one solution to achieving a task within the capabilities of most people (18 kg is less than AL = 18.4 kg). An equally acceptable solution would be to increase the load to 100 or more kg and provide mechanical lifting aids thus precluding manual handling and relieving the person of lifting altogether.

JOB PHYSICAL STRESS EVALUATION

The purpose of the job physical demands evaluation is to identify, quantify and document the physical stresses associated with a given job. This section outlines how such an evaluation should be performed so that the guidance of the previous section may be applied.

Selection of Analysts

All job analyses should be performed by an individual who has experience in work measurement and who is thoroughly familiar with the plant and the jobs done in it. The analyst should know the prescribed methods of performing these jobs and should be aware of all tasks (including any irregularly occurring tasks) associated with the job.

Selection of Employees

Only experienced employees who routinely perform their work according to job descriptions and who work at a normal pace should be selected for measurement during the job evaluation. This will assure that the job description accurately describes the work performed.

Selection of Jobs

Jobs should be rank ordered by incidence and severity rates of musculoskeletal disorders. Jobs with the highest rank should be studied first. The primary source used to formulate this sort of job ranking should come from medical information (if available) such as:

- medical reports
- first aid reports
- OSHA 101 forms
- worker's compensation payments

Things to look for on these reports include:

1. musculoskeletal injuries, particularly back injuries
    - overexertion
    - strains/sprains
    - contact injuries such as:
        - lacerations
        - bruises
        - abrasions
        - fractures

2. what job the injury occurred on so that a total for each job can be compiled

3. how much lost time was associated with each injury. In the absence of medical records, stressful jobs can be identified by information obtained from line supervisors or foremen for a particular job, such as:
    - is there a high turnover rate?
    - is there frequent absenteeism?
    - are there frequent sprain/strain complaints?

Analysis Procedures

All data collected should be organized on a "Physical Stress Job Analysis Sheet" (see Figure 8.2). The exact form is, of course, optional but it should include background and identification information for each job such as date, plant name, department, analyst's name and job title as well as the task descriptors to be measured. These are:

1. Weight of the object lifted - determined by direct weighing. If this varies from time to time, note the average and maximum weights.

2. The position of the load with respect to the body - this must be measured at both the starting and ending points of a lift in terms of horizontal and vertical location. The horizontal location from the body (H) is measured from the midpoint of the line joining the ankles to the midpoint at which the hands grasp the object while in the lifting position. The vertical component is

PHYSICAL STRESS JOB ANALYSIS SHEET

DEPARTMENT ____________________ DATE __________

JOB TITLE ____________ ANALYST'S NAME __________

TASK DESCRIPTION	OBJECT WEIGHT		HAND LOCATION				TASK FREQ	AL	MPL	REMARKS
			Origin		Destination					
	Ave	Max	H cm	V cm	H cm	V cm				

Figure 8.2: Example Coding Form.

determined by measuring the distance from the floor to the point at which the hands grasp the object. The coordinate system is illustrated in Figure 8.3.

These measures are repeated for the ending point of the lift (in the lifting position) and all four values are recorded on the job analysis sheet.

It these four values vary from task to task (e.g., stacking cartons on top of each other), the job must be separated into elements and each element evaluated. Examples later will suggest ways to handle such situations.

To be precise, the H value should be measured as described in item 2. However, a convenient rule of thumb is H = (W/2+15) cm or (W/2+6) in, where W = the distance of the load away from the body measured in the horizontal axis (fig. 8.3).

3. Frequency of lift - this should be recorded on the job analysis sheet in average lifts/min. for high frequency jobs. A separate frequency should be entered for each distinguishable job task.

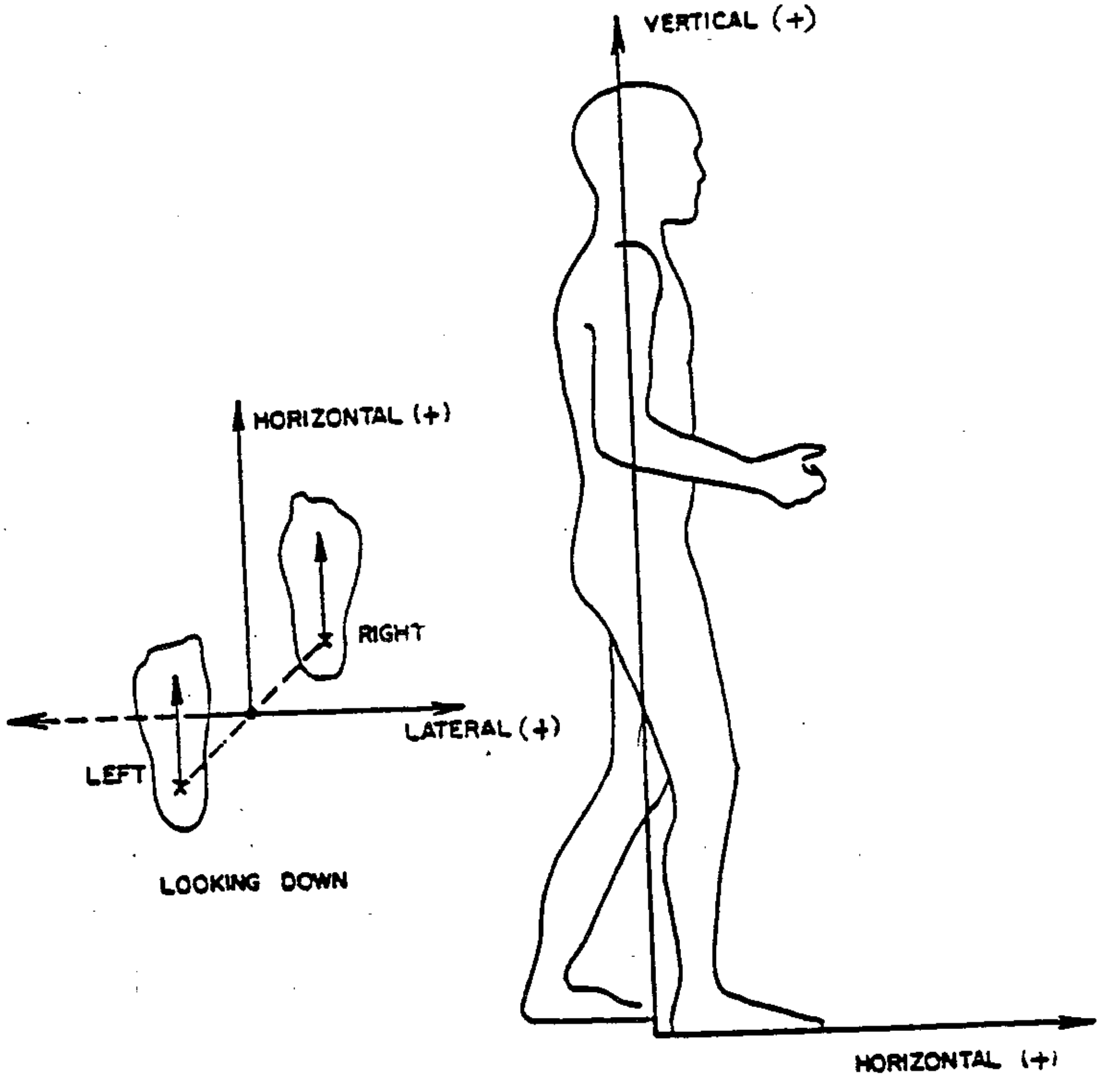


Figure 8.3 Graphic Representation of Vertical, Lateral and Horizontal Axes.

4. Period (or Duration) - the total time engaged in lifting should be noted. This need only be defined as less than one hour or more than one hour for the purposes of this Guide.

Figures 8.4 through 8.7 illustrate the factor weights for each of the above task variables. These nomograms allow the analyst to quickly determine the correct factor adjustments to be applied for each variable in order to complete the latter columns of the job

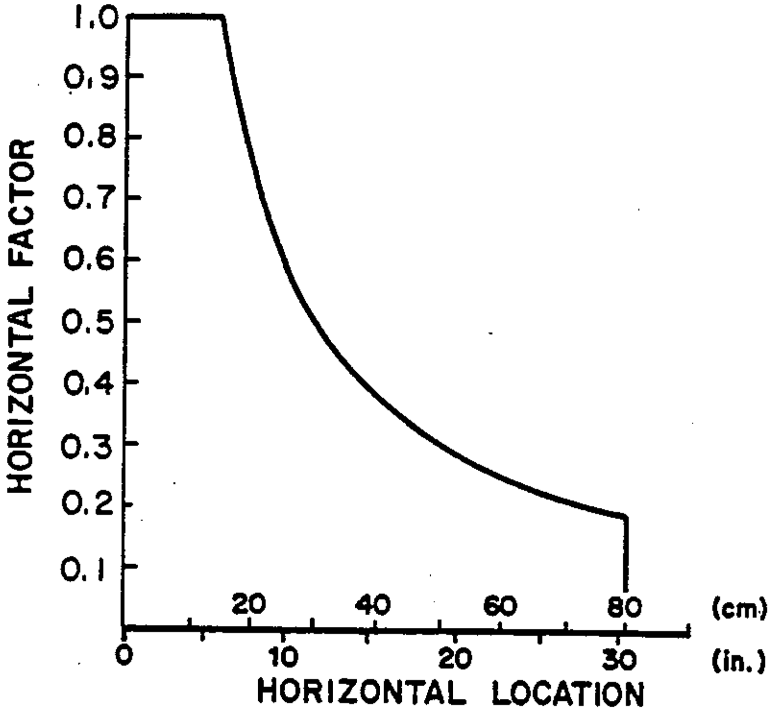


Figure 8.4: Horizontal Factor Nomogram.

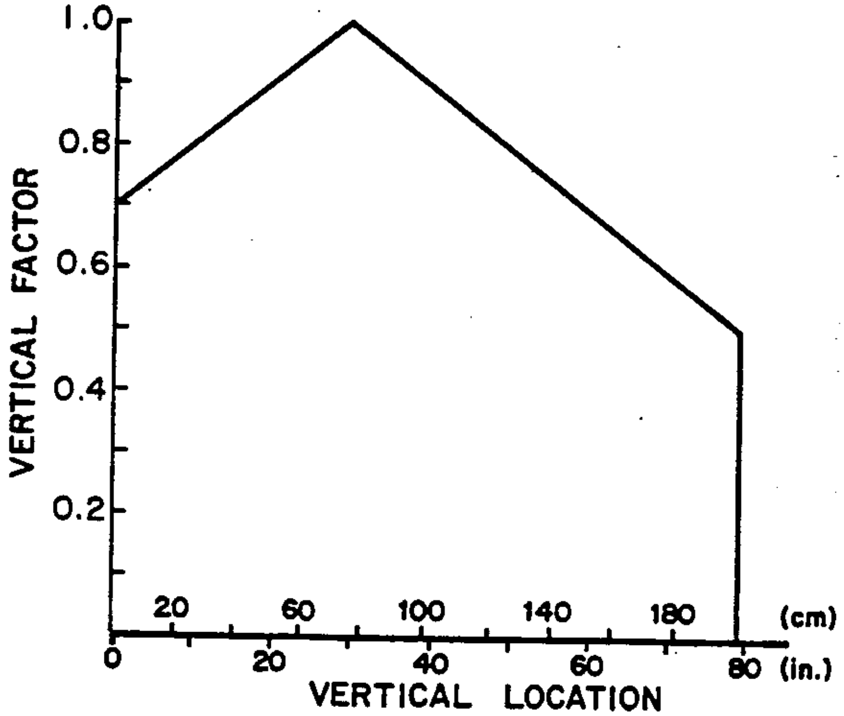


Figure 8.5: Vertical Factor Nomogram.

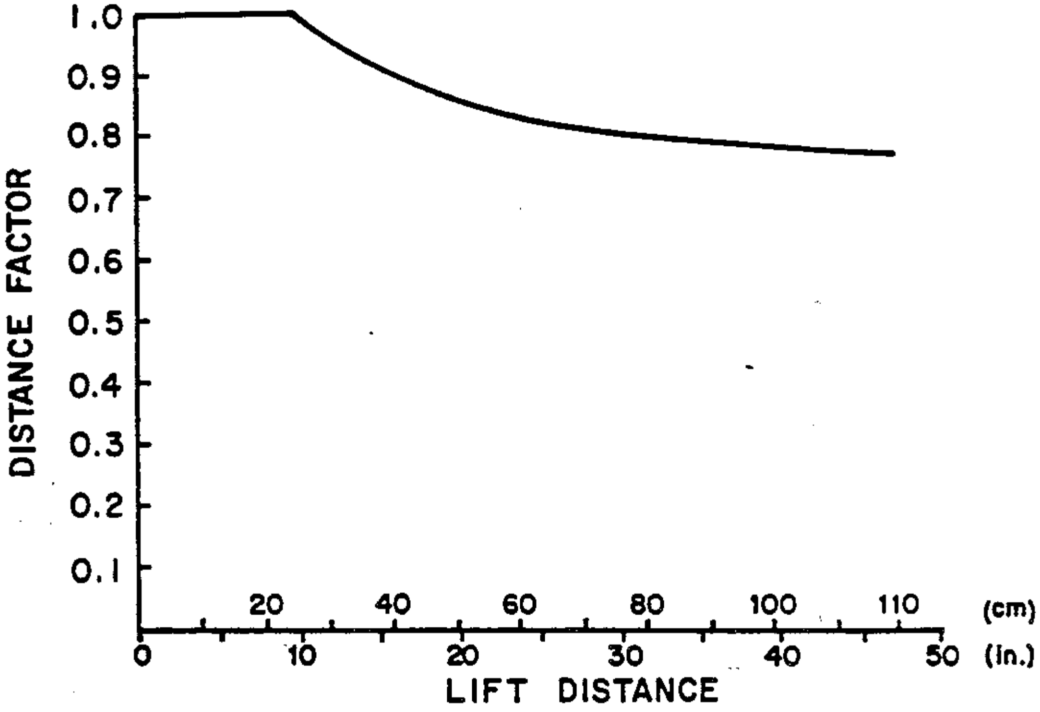


Figure 8.6: Vertical Distance Factor Nomogram.

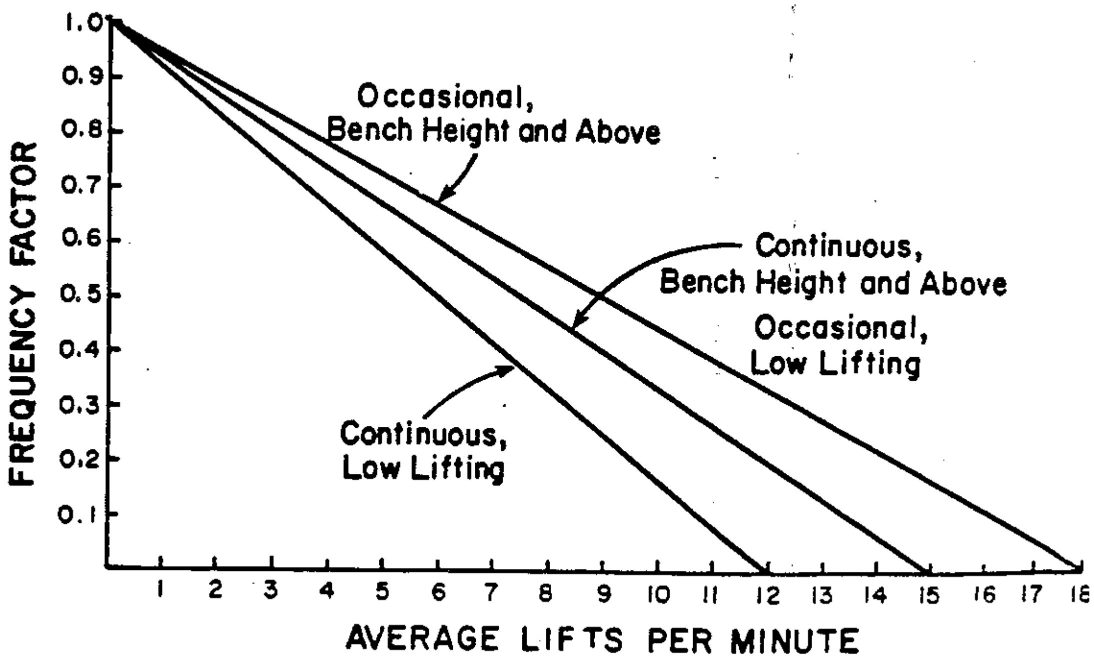


Figure 8.7: Frequency of Lift Factor Nomogram.

analysis sheet. The remarks section may be useful in describing which factor is most restrictive or limiting for each element.

EXAMPLES

Five examples will now be discussed to illustrate the analysis and interpretation of this methodology.

Example 1: Infrequent Lifting

Figure 8.8 illustrates a common misconception (or oversight) in terms of what types of jobs may be physically stressful. A punch press operator, for example, routinely handles small parts, feeding them in and out of a press. A cursory view of this task may overlook the fact that once per shift, the operator is required to load a reel of supply stock (illustrated shoulder height) from the floor onto the machine. The reel weighs 20 kg. This activity is documented in Figure 8.9. Assuming the operator lifts the reel in the plane shown (rather than on the side of the machine) the appropriate horizontal dimension is (75/2 + 15) = 53 cm or $(\frac{30}{2} + 6) = 21$ in. At the destination V = 160 cm (63 in). Since the activity occurs only once per shift, F = 0 (no frequency adjustment required).

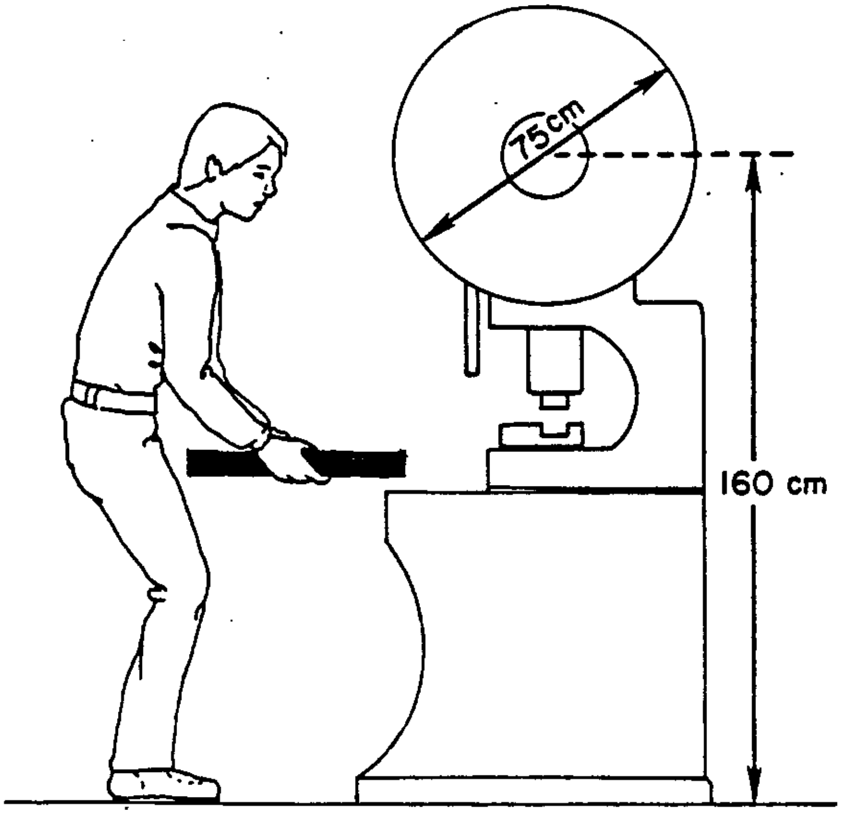
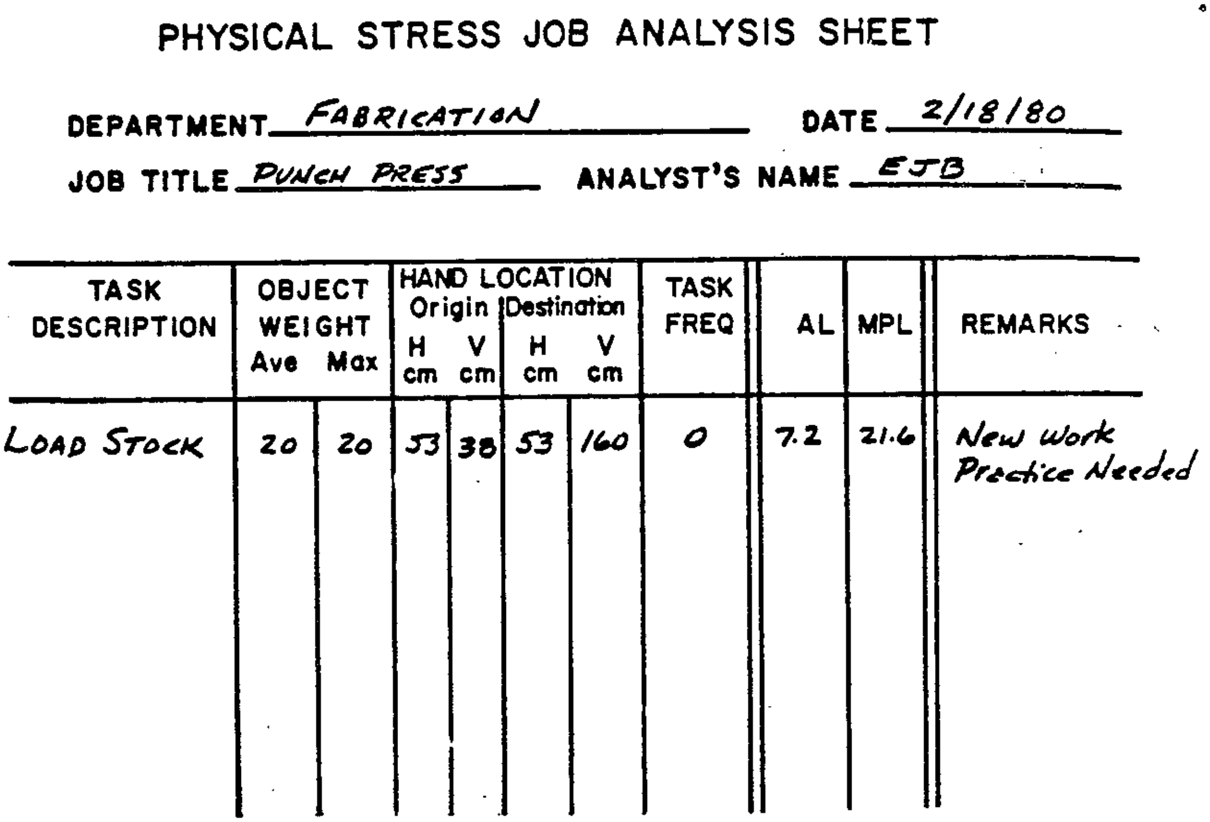


Figure 8.8: Example 1, Punch Press Operator.



PHYSICAL STRESS JOB ANALYSIS SHEET

DEPARTMENT FABRICATION DATE 2/18/80

JOB TITLE PUNCH PRESS ANALYST'S NAME EJB

TASK DESCRIPTION	OBJECT WEIGHT		HAND LOCATION				TASK FREQ	AL	MPL	REMARKS
			Origin		Destination					
	Ave	Max	H cm	V cm	H cm	V cm				
Load Stock	20	20	53	38	53	160	0	7.2	21.6	New Work Practice Needed

Figure 8.9: Job Analysis for Example 1.

Interpreting this activity in terms of the critical variables:

$$H \text{ factor} = 15/H = 15/53 = .28$$

$$D \text{ factor} = .7 + 7.5/(160-38) = .76$$

$$V \text{ factor} = 1 - .004\ (75-38) = .85$$

$$F \text{ factor} = 1 - 0/15 = 1.0$$

Therefore

$$AL = 40(.28)(.76)(.85)(1.0) = 7.2 \text{ kg}$$

$$MPL = 3(7.2) = 21.6 \text{ kg}$$

In this case, lifting the 20 kg reel in this way would be stressful for most people and at least strong administrative controls would be required if not engineering controls.

Notice that the H factor is most critical in this case (H factor = .28). If possible, the operator should load the machine from the side (i.e., grasping the reel by its perimeter). This would allow the reel to be brought closer to the body (i.e., H = 20 cm for example). With this preferred work practice,

$$AL = 40(.75)(.76)(.85)(1.0) = 19.4$$

$$MPL = 3(19.4) = 58.2$$

For all practical purposes the activity is now within the capabilities of most people. Alternative engineering controls might include elevating the delivery of reels (above the floor) thus improving both the V and D factors.

Examples 2 and 3: H Not Constant

Evaluation of jobs where the H value is not constant throughout the lift should be approached with caution by the analyst. The most common error is to exaggerate H, making a job seem more difficult than it actually is.

For example, a compact load is lifted from the floor to a point 125 cm high as illustrated in Figure 8.10. Due to workplace constraints the object must be placed on a moving conveyor at a distance H=80 cm but the lift is unconstrained up to waist height (about 100 cm). In most cases, the load can be lifted close to the body up to this point and then through transfer of momentum be placed on the conveyor with little difficulty. Using an H value of 80 cm greatly overestimates the strength requirements of this task. As a general rule of thumb, the analyst should use the H value at the origin (in this case close to the body) to determine the weight limit and not the H value for the end point of the lift. However, a fragile load that must be carefully handled throughout the lift may well require the strength capabilities of lifting the load from the floor to the end point at an H value equal to that of the end point!

The estimation of horizontal location as W/2 + 15 cm for body clearance is not appropriate with horizontal obstructions such as illustrated in Figure 8.11. In this case, the appropriate horizontal dimension is 60 cm at the origin. Presumably the load is not fragile, nor need it be retrieved from the destination. If it must be retrieved the horizontal location at the destination will become the origin for a subsequent lift!

Example 4: Occasional High Frequency Lifting of Constant Weights

Suppose that for a period of one hour, a person unloads palletized cartons each weighing 5 kg stacked 5 high onto a conveyor as illustrated in Figure 8.12. In this case the vertical origin location

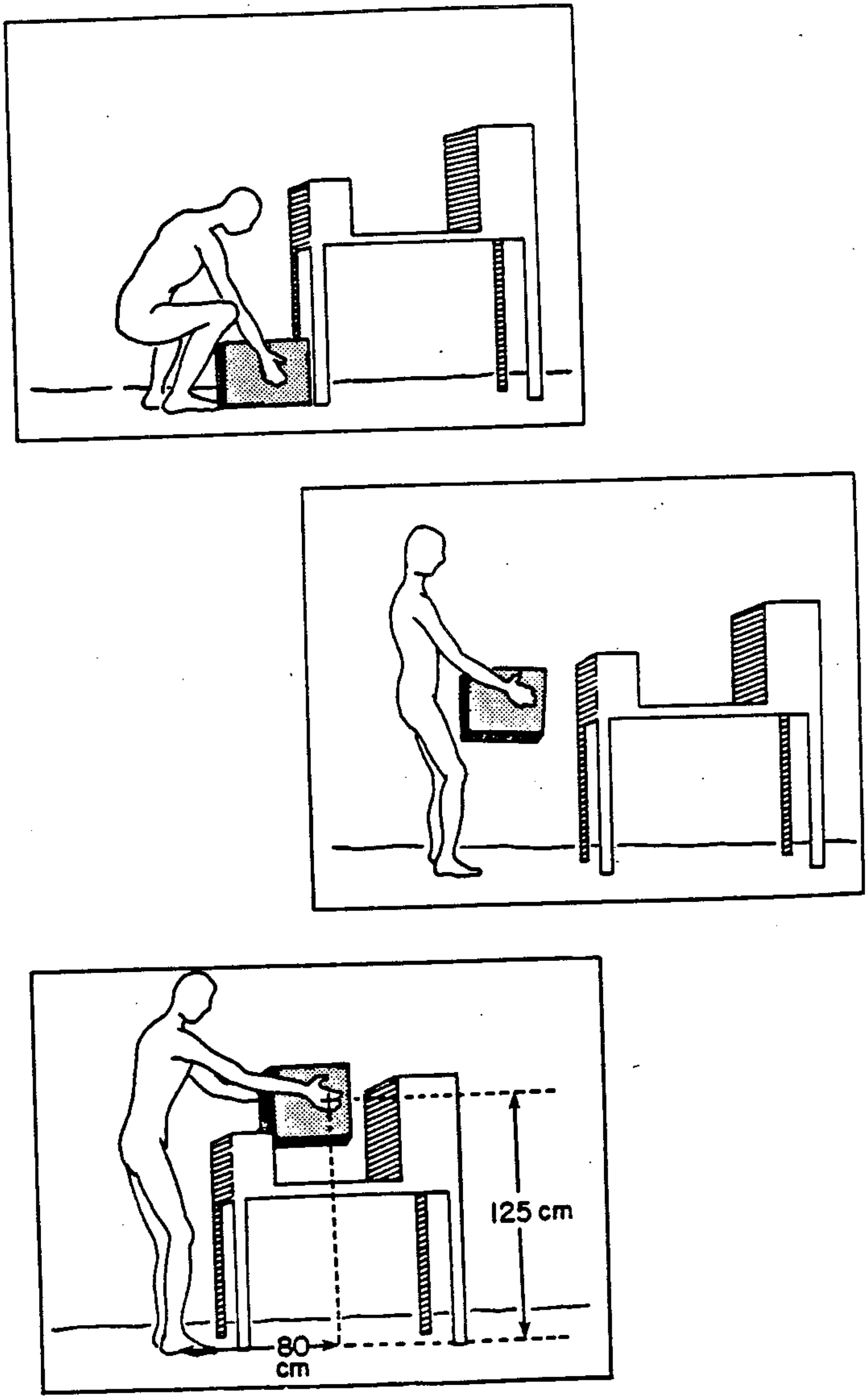


Figure 8.10: Example 2, Transfer of Momentum.

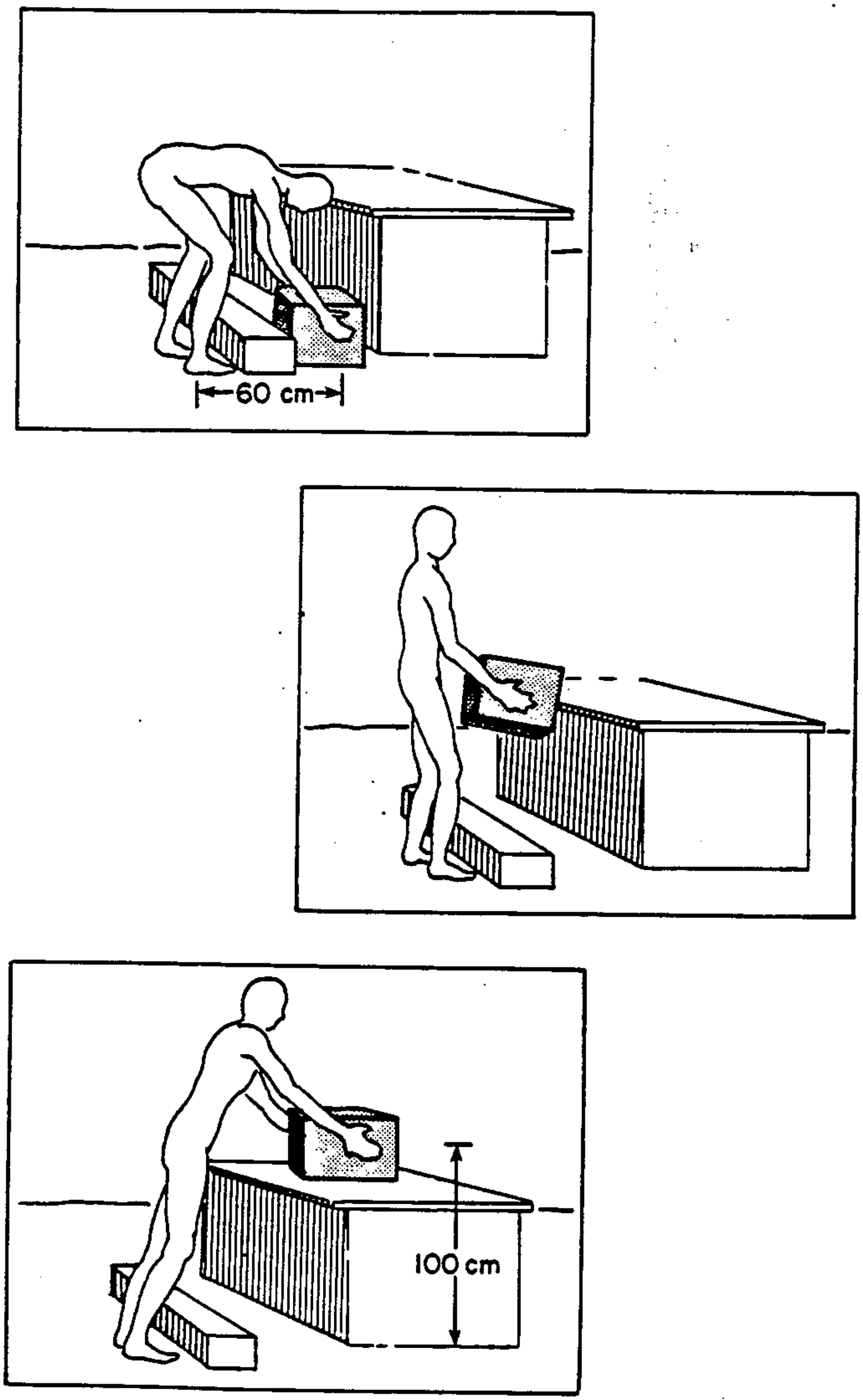


Figure 8.11: Example 3, Horizontal Obstruction.

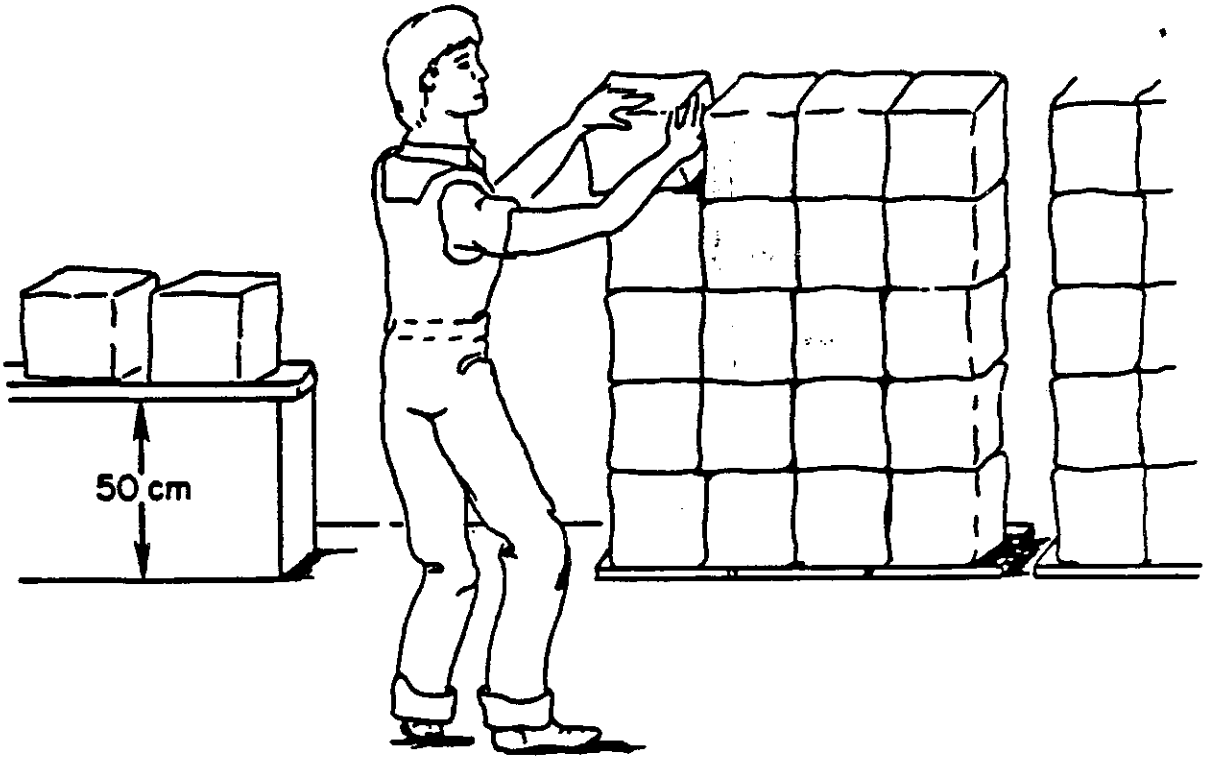


Figure 8.12: Example 4, Depalletizing Operation.

(V) and vertical travel (D) vary from one lift to the next. Also note that this task requires both lifting and lowering (for those high cartons) as well as possibly some twisting and carrying. These later aspects are outside this Guide and their effects should be minimized by a slowed pace for lifting and delivering pallets as close to the conveyor as possible.

Figure 8.13 presents an analysis which approximates the stresses of this activity assuming the carton dimensions are 40 cm x 40 cm x 40 cm, unloaded 12 per minute, and the person is free to climb over the pallet to get close to each carton. Basically the job is divided into 5 tasks representing the 5 tiers of the loaded pallet. The base frequency (12/min) is divided between each tier (2.4 lifts/min/tier). The horizontal location is estimated as H = (15 + 40/2) = 35 cm. The vertical locations at the origin represent the position of the hands under the cartons (ignoring the pallet height for purposes of this example).

Two separate analyses are warranted in this case. Each task should be analyzed separately and then collectively. The most stressful task (or tier) is task 5. For this task the V factor = (1 - .004(160-75)) = .66. The V factors for each of the other tasks will

PHYSICAL STRESS JOB ANALYSIS SHEET

DEPARTMENT WAREHOUSE DATE 8/8/80

JOB TITLE DEPALLETIZING ANALYST'S NAME GDH

TASK DESCRIPTION	OBJECT WEIGHT		HAND LOCATION				TASK FREQ	AL	MPL	REMARKS
			Origin		Destination					
	Ave	Max	H cm	V cm	H cm	V cm				
UNLOAD PALLETS							12/MIN			
TIER 1	5	5	35	0	35	50	2.4			
TIER 2	5	5	35	40	35	50	2.4			
TIER 3	5	5	35	80	35	50	2.4			
TIER 4	5	5	35	120	35	50	2.4			
TIER 5	5	5	35	160	35	50	2.4	8	24	
TOTAL	5		35	80			12	4.7	14	

Figure 8.13: Example 4, Analysis Sheet.

be larger since this vertical origin is most distant from 75 cm. Note that with more complicated tasks such a simplification will not necessarily be possible. It is only possible with this job since all other variables remain constant.

For this most stressful task, then

$$AL = 40\ (15/35)(.66)(.7+7.5/110)(1-2.4/18) = 8\ \text{kg}$$

$$MPL = 3\ (8) = 24\ \text{kg}$$

It is concluded that individually the elements of the job are quite reasonable (5 kg is below the AL).

Now consider the tasks collectively. The following approximation is not exact but should provide a reasonable composite estimate. Derive a weighted average for each variable in the job analysis according to frequency. In this case frequency is constant across tasks and vertical origin and travel distance are the only factors which vary.

The average vertical location is

$$V = \frac{0 + 40 + 80 + 120 + 160}{5} = 80 \text{ cm}$$

The average vertical travel is

$$D = \frac{50 + 10 + 30 + 70 + 110}{5} = 54 \text{ cm}$$

For the total job then

$$AL = 40\ (15/35)(1-.004(5))(.7+7.5/54)(1-12/18)$$

$$= 40\ (.43)(.98)(.84)(.33)$$

$$= 4.7 \text{ kg}$$

$$MPL = 14 \text{ kg}$$

Since the carton weight (5 kg) is nominally above the AL, administrative controls may be required. The analysis suggests that the problem with this job is not so much strength (at issue in the individual task analysis) but endurance. Since a number of simplifying assumptions were made in this analysis a more detailed metabolic analysis of such a job may be warranted before implementing administrative controls. Such an analysis is described in detail by Garg, et al., (1978).

Example 5: Continuous High Frequency Lifting, Variable Tasks

Lifting tasks of this type are typical in warehousing, shipping and receiving activities where there are many different sized loads of varying weights that are lifted at varying frequencies. As a simple example, consider a job with the set of 3 tasks described in Figure 8.14.

For highly variable jobs (such as this one) this Guide is most limited. Following the procedure of the preceding example, each task should first be examined individually. The recommended AL and MPL for each task is as follows:

TASK 1: $AL = 40\ (15/40)(1-.004(75))(.7+7.5/75)(1-1/12)$

$$= 40\ (.38)(.70)(.80)(.92) = 7.8$$

$$MPL = 23.4$$

PHYSICAL STRESS JOB ANALYSIS SHEET

DEPARTMENT Receiving **DATE** 5/1/80

JOB TITLE Loader **ANALYST'S NAME** CKA

TASK DESCRIPTION	OBJECT WEIGHT		HAND LOCATION				TASK FREQ	AL	MPL	REMARKS
			Origin		Destination					
	Ave	Max	H cm	V cm	H cm	V cm				
Product A	10	40	40	0	50	75	1	7.8	23.4	Reduce product variability
Product B	15	30	30	0	30	15	2	11.6	34.8	
Product C	5	10	15	75	20	100	5	26.8	80.4	
Total	8.1		22	47			8	7.7	23.1	

Figure 8.14: Example 5, Highly Variable Job.

TASK 2: $AL = 40\ (15/30)(1-.004(75))(.7+7.5/25)(1-2/12)$

$= 40\ (.50)(.70)(1.0)(.83) = 11.6$ kg

$MPL = 34.8$

TASK 3: $AL = 40\ (15/15)(1-.004(0))(.7+7.5/25)(1-5/15)$

$= 40\ (1.0)(1.0)(1.0)(.67) = 26.8$ kg

$MPL = 80.4$ kg

Two technical aspects of the above calculations are noteworthy:

a. Travel distances less than 25 cm should be considered as 25 cm. In task 2, this cutoff was used. (Factors must all be less than or equal to 1.0).

b. Since this job is performed continuously, F_{max} factors (from Table 8.2) of 12 and 15 were used for lifts from less than and greater than 75 cm.

Based on this elemental analysis it can be concluded that Tasks 1 and 2 are the most stressful. In fact, the maximum weights of 40 kg (Task 1) are above the MPL = 23.4 and engineering controls (such as mechanical aids or two-person lifting) are warranted. Note that the average weights in Task 1 (10 kg) are reasonable with administrative controls. In both cases, the horizontal location produces the greatest discount in ability. Task 3 appears to be nominal in terms of physical stress.

As with Example 4, analysis of the combined elements of the job can only be approximated by computing weighted averages according to frequency. In this case, the composite

$$H = \frac{1(40) + 2(30) + 5(15)}{8} = 22 \text{ cm}$$

The coefficients 1, 2, and 5 correspond to each elemental frequency and 8 is the total number of lifts per minute.

Similarly, the weighted average

$$V = \frac{1(0) + 2(0) + 5(75)}{8} = 47$$

$$D = \frac{1(75) + 2(15) + 5(25)}{8} = 29$$

$$F = 1 + 2 + 5 = 8$$

Thus, for the combined tasks:

$$AL = 40\ (15/22)(1-.004(75-47))(.7+7.5/29)(1-8/12)$$

$$= 40\ (.68)(.89)(.96)(.33) = 7.7 \text{ kg}$$

$$MPL = 23.1 \text{ kg}$$

Since the average weight lifted is 8.1 kg, administrative controls are required.

It is important to note that this "averaging" of the task descriptors in this case tends to dampen out the large differences between the tasks. This is true in general (but not always). This error and the errors introduced by ignoring other carrying, holding, pushing, and pulling tasks can only be resolved with more detailed biomechanical, metabolic, and psychophysical evaluations.

ADMINISTRATIVE CONTROLS

Given the preceding detailed analysis of the physical stresses, a lifting job (or tasks within a job) can be classified into one of 3 zones:

1. Acceptable (below the AL),
2. Unacceptable for most individuals (above the MPL), or
3. Unacceptable for some individuals (between the AL and MPL).

This section deals with selecting and training of workers for jobs of the latter type (3). A more detailed discussion is presented in Chapter 6. Alternative engineering controls are then summarized for conditions 2 and 3. A more detailed discussion appears in Chapter 7.

Selection

In order to safely match a worker to the physical demands of a given task, several selection procedures can and have been used. For the many manufacturing, distribution, and service industries which have no medical staff, self-selection has been the principal method. Other methods commonly used are:

1. Questionnaires on health and medical history
2. Tests of visual, auditory and pulmonary function, blood pressure, mobility and a chest X-ray
3. Clinical examination.

The problem with these is that they are unreliable predictors of medical risk of injury. Also, the worker is usually not followed medically during the first few weeks of training when many postural stress related problems could be prevented.

In view of these problems, routine lumbar spinal radiography has often been prescribed by occupational medical advisors as a prerequisite for employment in heavy manual work. Using X-rays for this purpose, however, is very controversial because:

1. There have not been any statistically significant differences shown in the incidence of radiological abnormalities between workers with known history of back pain and those without.
2. There is a problem of X-ray interpretation. No reliable data exists on the predictive rating for observed abnormalities. It is also impossible to quote a value for the increased probability of back trouble for different abnormalities.

3. X-rays present a radiation hazard, particularly for females who cannot be given adequate gonadal protection.

In summary, caution must be exercised in using the lumbar spinal radiograph as a selection tool. If so, it should be performed by an experienced physician after a thorough interview and examination, and with full knowledge of the MMH job concerned.

Physical Assessment of Workers

What is needed is an objective means for assessing the physical capabilities of a worker who is being considered for a certain job. In providing such an assessment certain medical, social and economic criteria must be met, these are:

1. Is it safe to administer?
2. Does it give reliable, quantitative values?
3. Is it related to specific job requirements?
4. Is it practical?
5. Does it predict the risk of future injury or illness?

As we have seen, the low back X-ray fails to some degree in each of these criteria, particularly in those relating to safety and reliability. As an alternative, worker strength testing and aerobic capacity testing have been proposed as means to meet these objectives. If carefully administered they appear to satisfactorily meet each of the above criteria as discussed in Chapter 6.

Training

The importance of training in manual materials handling in reducing hazard is generally accepted. What is lacking, however, is a clear definition of what the training should be and how it should be taught. Most controlled studies of training have shown it to be ineffective in reducing accidents and injuries related to lifting. Despite this, however, some form of training in manual materials handling jobs is likely to continue. What follows is a suggestion of what a training program should include.

1. What should be taught.

   The aims of training for safety in lifting should be:

   a. To make the trainee aware of the dangers of careless and unskilled lifting.

   b. To show them how to avoid unnecessary stress.

c. To teach the worker individually to become aware of what he/she can handle comfortably without undue effort.

In order for the training to be effective, the instructors must be well versed in the sciences basic to manual materials handling and in Safety Engineering. The content of the course must also be suited to the educational background of the trainees.

The course should cover the following aspects:

a. <u>The risks to health of unskilled lifting</u>: Case histories from the organization concerned provide the best illustration.

b. <u>The basic biomechanics of lifting</u>: The body as represented by a system of levers.

c. <u>The effects of lifting on the body</u>: The basic anatomy of the spine and the muscles and joints of the trunk; the contribution of intra-thoracic pressure while lifting.

d. <u>Individual awareness of the body's strengths and weaknesses</u>: How to estimate one's comfortable lifting capacity.

e. <u>How to avoid the unexpected</u>: Recognition of the physical factors which might contribute to an accident.

f. <u>Handling skill</u>: Safe lifting postures; minimizing the load - moment effects; timing for smooth and easy lifting.

g. <u>Handling aids</u>: Platforms, stages or steps, trestles, handles, wheels, shoulder pads.

h. <u>Warnings</u>: What to be aware of when lifting.

2. <u>How it Should be Taught</u>.

It is not enough to teach safe lifting practices by slides or films. The trainee should be practically involved from the start. Therefore, classes must be small. Training should not be restricted to a classroom. Lifting technique should be demonstrated and practiced at the work site. Supervisors, as well as trainees, should be involved in the training program. The following are the steps to an effective training program:

a. Begin with a poster campaign drawing attention to the need to do something about lifting accidents and back injuries, changing them every few days.

b. Organize a training session for managers and supervisors.

c. Present the training course to small groups of employees.

d. Have the plant doctor and the team of instructors tour the plant, discussing any points put to them by the workers.

e. Continue to make plant tours at regular intervals.

In summary, there is a vital need for training to be both in the classroom and on the site, to involve all levels of workers including executives, and to be monitored routinely throughout the factory in order for the program to be effective.

ERGONOMIC/ENGINEERING CONTROLS

More important than proper selection and training in the long term prevention of accidents and injuries related to lifting, is providing a safe ergonomic environment in which to work. This includes factors of the mechanical environment (such as container design, human/container coupling design, worker/floor surface coupling), the visual environment and the thermal environment.

Mechanical Environment

1. Container Design. From the biomechanical considerations discussed in Chapter 3, containers should be as small as possible. A compact load minimizes the compressive forces applied to the L_5/S_1 disc because the load center of gravity can be brought close to the spinal column - oftentimes between the legs, which reduces disc pressure even more. Another important factor in container design is the load center of gravity. Baffles, dividers or packing should be used to keep the center of gravity in a constant position because any shifting of the load could contribute to human error in manual handling.

   Anthropometry plays an important part in recommending the maximum dimension of a container. If the forward edge is to be reached, the length should not exceed 70 cm (males) or 65 cm (females). To prevent interference with forward vision, the maximum height of the container above handle position should be 83 cm (males) and 80 cm (females). Also handles should be placed so that the whole container is above hip height when the elbows are extended.

2. Human/Container Coupling Design. Handles on containers should be designed with the worker's hand in mind. They have a large effect on both the maximum force a worker can exert on a container and on the energy expenditure in manual materials handling tasks. The major problems with most handles are insufficient hand clearance, sharp edges which can cut into the hand and too small of a handle diameter.

   The postures of the hand with respect to grasped objects can be classified as follows:

   a. Hook grip. One in which the fingers are flexed around the object and the thumb is not used for gripping.

   b. Power grip. One in which the object is clamped between the partly flexed fingers and palm with the thumb opposing the grip and lying along the plane of the palm.

   c. Precision grip. One in which the object is pinched between the flexor aspects of the fingers and opposing thumb.

   Most handles force the worker to use the hook grip (the least effective) or the power grip. The power grip gives a good gripping force and allows a large surface of the hand to be used but often is inefficient if accurate control is needed. The weight of the object often prevents the precision grip from being used.

   There is little agreement in the literature as to what the optimum handle diameter is, but from 25 mm (1 inch) to 38 mm (1.5 in.) is the range into which most recommendations fall. The elimination of sharp edges, seams, rubbing, and corners appears to be of more importance than actual handle diameter. The shape of the handle is better cylindrical than molded to the contours of the hand.

   Handle width should be at least 11.5 cm (4.5 in.) with 50 mm (2 inches) clearance all around the handle to accommodate a 95th percentile hand. If gloves are used, at least 25 mm (1 inch) should be added to these dimensions.

3. Worker/Floor Surface Coupling. Poor worker/floor coupling will most often result in accidents such as slips, trips, or missteps. The major mediating variable in these types of accidents is the coefficient of friction between the shoe sole and the working surface. This can be affected by:

a. work surface materials

b. surface coating

c. floor condition

d. floor angle

e. shoe sole/heel composition and contact area

f. shoe style

The general recommendation is to adjust shoes and working surfaces to give a coefficient of static friction of at least .4 and preferrably .5.

Unnoticed changes in surface friction can also cause accidents. These can be reduced by:

a. ensuring that different surface materials or coatings have transition zones between them,

b. clearly marking any surface friction change,

c. using good housekeeping procedures to reduce transient changes in surface friction such as spills, worn spots, loose or irregular floors.

Because of the forces transmitted from the container to the body when lifting, good work/floor coupling is essential in controlling accidents and injuries resulting from foot slippage.

The Visual Environment

While manual materials handling operations rarely demand the fine visual discrimination of delicate assembly work, they do require control of the visual environment for optimum performance and safety. The task of lifting involves vision of the container, the workplace around the container and the surface on which the operator stands. An illuminance of 150 lux (14 foot-candles) in each of these areas is a recommended minimum.

Types of lifting can have a large effect on visual performance, particularly in the areas of depth perception and surface texture perception. Differences in contrast or differential illumination can be used to make stairs or changes in walking surfaces easily discernible. Low, angled illumination is recommended for enhancing surface texture to warn operators of changes in shoe/surface friction. Depth perception errors can be controlled by changing reflectance of the container and task to provide additional contrast. Color contrast can be used on edges of steps, loading docks and ramps when the consequences of misperception are severe.

Labeling can be used to indicate handhold positions, cautions against single person lifting if the load is heavy, or a note of caution if its center of gravity is not near the center or if it is likely to shift.

The Thermal Environment

Deviations from the comfort zone (18°C (64.5°F) to 21°C (70°F) have been shown to influence injuries in many industries. It is thus particularly important to ensure that thermal stress does not contribute to manual materials handling safety problems.

Cold environments are not usually a problem in manual materials handling because the strenuous nature of the work provides sufficient heat production, and the thermal clothing may provide some personal injury protection. The cold, however, does reduce dexterity which could lead to human error in lifting.

If a heat stress problem is suspected, it should be assessed by the Wet Bulb Globe Temperature (WBGT) index. Recommendations for this index can be found in the ACGIH (1980). Engineering control measures such as radiant heat shielding, forced air movement, clothing design and work-rest schedules can be used to prevent body temperatures from increasing over the 38°C (100.4°F) recommendation.

Materials Handling System Alternatives

Jobs which exceed the MPL should be performed with the aid of some mechanical device or redesigned so that they can be performed safely. Some examples of simple lifting aids found at the workplace are:

a. Hooks: The worker should be trained in the use of handling packing hooks so that they will not glance off hard objects.

b. Bars: The major hazard of a crow bar is that it may slip. The edge should have good "bite".

c. Rollers: These are effective in moving heavy and bulky objects.

d. Jacks: They should be marked to indicate the safe load which can be raised.

e. Platforms: These provide the maintenance of a convenient height for lifting and handling.

f. Trestles: These can be used to maneuver long loads on the point of balance, or for readjusting the grip or carrying posture.

Other types of mechanical aids are:

a. Conveyors are used primarily when loads are uniform, movement is from one point to another, and materials move constantly.

b. Cranes and Hoists are most commonly used when loads vary in size and weight, moves are intermittent, and cross traffic will interfere with conveyors.

c. Industrial trucks are most often used when materials are moved intermittently, over varying routes, when cross traffic would prohibit conveyors, and loads are uniform or mixed in size and weight.

Potential Safety and Ergonomic Problems

Reducing the physical hazards or manual lifting to the musculoskeletal system can often result in other types of safety problems. Some of these are:

a. Conveyors: Aside from mechanical entrapments, the major problem with conveyors is that the work is externally paded. This can cause time-stress induced errors. Conveyor designs which take into account the cycle-to-cycle variability of the operator can reduce such stress. Buffer stocks between stations achieve the same effect.

b. Cranes and Hoists: Because of the dangers involved when a load is suspended, cranes are among the most hazardous of material handling equipment. The crane cab and all controls should be designed for good visibility and safe operation. The loading capacity of the crane should be clearly marked. Standard signals should be used between the crane operator and the signalman on the ground.

c. Hand Trucks: Safety hazards include falling of the load, collision between the truck and other objects, and the operator getting pinned between the truck and another object. These can be reduced by such design features as: covering all exposed handles with knuckle guards, guarding or recessing all wheels, brakes that apply automatically when the handle is either fully raised or fully lowered, or released.

CONCLUSION

It has been traditional to bemoan the existence of widely divergent recommendations for maximum weights which can be safely lifted. These divergent recommendations have actually been due to the differences in what is accepted as a reasonable criterion by different scientific disciplines. This Guide has attempted to integrate the conclusions of four distinctive disciplines within the broad field of Ergonomics into one set of recommendations. Obviously, the recommendations do not satisfy any of the criteria perfectly and considerable qualification of the specific aspects of lifting were required in order to arrive at any consensus.

The convergence between the methodologies, however, overshadows the differences. The fact that these technologies agree on the major factors which limit lifting ability and even point to similar absolute magnitudes is strong evidence that the guidance is sound. This guidance will only be effective, though, if it is carefully studied and applied within your workplace.

REFERENCES

Aberg, U. "Physiological and Mechanical Studies of Material Handling." Ergonomics Research Society Annual Conf., 1961.

Aberg, U.; Elgstrand, K.; Margnus, P. and Lindholm, A. "Analysis of Components and Prediction of Energy Expenditure in Manual Tasks." Int. J. Prod. Res. 6:189-196, 1968.

ACGIH. Threshold Limit Values for Physical Agents. Adopted by ACGIH for 1980. p 58.

Ad Hoc Committee on Low Back X-Rays. "Low Back X-Rays: Criteria for Their Use in Placement Examinations in Industry." J. Occup. Med. 6:373-380, 1964.

Alston, W.; Carolson, K.E.; Feldman, D.J. Grimm, Z and Gerontinos, E. "A Quantitative Study of Muscle Factors in the Chronic Low Back Syndrome." J. Am. Geriat. Soc. 14:1041-1047, 1966.

American Heart Association. Exercise Testing and Training of Apparently Healthy Individuals. A Handbook for Physicians, 1972.

American Industrial Hygiene Association. "Ergonomics Guide to the Assessment of Metabolic and Cardiac Cost of Physical Work." Am. Ind. Hyg. Assoc. J. 32:560-564, 1971.

Anderson, T.N. "Human Kinetics in Strain Prevention." J. Occup. Safety. 8:248, 1970.

Apple, J.M. "Materials Handling." In: Industrial Engineering Handbook. H.B. Maynard, Ed., McGraw Hill, New York, 1971. Chapt. 11.5.

Aquilano, N.J. "A Physiological Evaluation of Time Standards for Strenuous Work as Set by Stopwatch Time Study and Two Predeternimed Motion Time Data Systems." J. Indust. Eng. 19: 425-432, 1968.

Armstrong, J.R. Lumbar Disc Lesions. Williams and Wilkins Co., Baltimore, 1965.

Asmussen, E. and Heeboll-Nielsen, K. "Isometric Muscle Strength of Adult Men and Women." Communications from Testing and Observation Institute of the Danish National Association for Infantile Paralysis. 11:1-44, 1961.

Asmussen, E. and Heeboll-Nielsen, K. "Isometric Muscle Strength in Relation to Age in Men and Women." Ergonomics, 5:167-169, 1962.

Astrand, I. "Aerobic Work Capacity in Men and Women with Special Reference to Age." *Acta. Physiol. Scand*. 49(Suppl. 169), 1960.

Astrand, I. "Degree of Strain During Building Work as Related to Individual Aerobic Work Capacity." *Ergonomics*. 10:293-303, 1967.

Astrand, P.O. and Rodahl, K. *Textbook of Work Physiology*. McGraw Hill, New York, 1970.

Astrand, I.; Astrand, P.O.; Hallback, I. and Kilbon, A. "Reduction in Maximal Oxygen Uptake with Age." *J. Appl. Physiol*. 35: 649-654, 1973.

Ayoub, M.A. "Optimum Design of Containers for Manual Materials Handling Tasks." *Appl. Ergonomics*. 8:67-72, 1977.

Ayoub, M.A. and LoPresti, P. "The Determination of Optimum Size Cylindrical Handles by Use of EMG." *Ergonomics*.14:509-518, 1971.

Ayoub, M.M.; McDaniel, J.W. and Dryden, R.D. "Modeling in Lifting Activities." Paper presented at the American Industrial Hygiene Association Meeting, 1973.

Ayoub, M.M. and McDaniel, J.W. "Predicting Lifting Capacity." Paper presented at the Fifth Congress on Ergonomics, Amsterdam, Holland, 1973.

Ayoub, M.M. and McDaniel, J.W. "Effects of Operator Stance on Pushing and Pulling Tasks." *AIIE Transactions*. 6:185-195, 1974.

Ayoub, M.M.; Dryden, R.D. and Knipfer, R.E. "Psychophysical Based Models for the Prediction of Lifting Capacity of the Industrial Worker." Paper presented at the Automotive Engineering Congress and Exposition (SAE), Detroit, 1976.

Ayoub, M.M.; Dryden, R.D.; McDaniel, J.W.; Knipfer, R.E. and Aghazadeh, F. "Modeling of Lifting Capacity as a Function of Operator and Task Variables." In: *Safety in Manual Materials Handling*. C.G. Drury, Ed. DHEW(NIOSH) Publication No. 78-185, 1978a. pp 120-130.

Ayoub, M.M. and El-Bassoussi, M.M. "Dynamic Biomechanical Model for Sagittal Plane Lifting Activities." In: *Safety in Manual Materials Handling*. C.G. Drury, Ed. DHEW(NIOSH) Publication No. 78-185, 1978b. pp 88-95.

Ayoub, M.M.; Bethea, N.J.; Deivanayagam, S.; Asfour, S.S.; Bakken, G.M.; Liles, D.; Mital, A. and Sherif, M. "Determination and Modeling of Lifting Capacity." Final Report, DHEW(NIOSH) Grant 5 RO1 OH 00545-02, 1978c.

Backlund, L. and Nordgren, L. "A New Method for Testing Isometric Muscle Strength under Standardized Conditions." Scand. J. Clin. Lab. Invest. 21:33-41, 1968.

Bartelink, D.L. "The Role of Abdominal Pressure in Relieving the Pressure on the Lumbar Intervertebral Discs." J. Bone Joint Surg. 39B:718-725, 1957.

Becker, W.F. "Prevention of Back Injuries through Preplacement Examinations." Indust. Med. Surg. 24:486-490, 1955.

Becker, W.F. "Prevention of Low Back Disability." J. Occup. Med. 3:329-335, 1961.

Berenson, P.J. and Robertson,W.G. "Temperature." In: Bioastronautics Data Book. 2nd Ed., J.F. Parker and V.R. West, Eds. NASA, 1973. Chapt. 3.

Bernauer, E.M. and Bonanno, J. "Development of Physical Profiles for Specific Jobs," J. Occup. Med. 17:27-33, 1975.

Bink, B. "The Physical Working Capacity in Relation to Working Time and Age." Ergonomics. 5:25-38, 1962.

Bink, B. "Additional Studies on Physical Working Capacity in Relation to Working Time and Age." Proc. Second Internat. Cong. Ergonomics, Dortmund, 1964.

Blow, R.J. and Jackson, J.M. "Rehabilitation of Registered Dock Workers." Proc. Roy. Soc. Med. 64:753-760, 1971.

Bobbert, A.C. "Optimal Form and Dimensions of Hand-Grips on Certain Concrete Building Blocks." Ergonomics. 2:141-147, 1960.

Bonjer, F.H. "Actual Energy Expenditure in Relation to the Physical Working Capacity." Ergonomics. 5:29-31, 1962.

Bonjer, F.H. "Temporal Factors and Physiological Load." In: Measurement of Man at Work, W.T. Singleton, J.G. Fox and D. Whitfield, Eds. Taylor and Francis, Ltd., London, 1971.

Borg, G.A.V. Physical Performance and Perceived Exertion. Ejnar M. Munksgoard, Copenhagen, 1973.

Borg, G.A.V. "Perceived Exertion: a Note on 'History' and Methods." Med. Sci. in Sports. 5:90-93, 1973.

Braun, R. and Roemer, D. "Influence of Waxes on Static and Dynamic Friction. Soap, Cosmetics, Chemical Specialties, West Germany, 60-72, 1974.

Brouha, L. "Role of Climatic and Environmental Conditions in Weight Carrying." Indust. Med. Surg. 36:257-266, 1967.

Brown, J.R. Lifting as an Industrial Hazard. Labour Safety Council of Ontario, Ontario Dept. Labor, Ontario, Canada, 1971.

Brown, J.R. "The Contributory Factors to the Development of Low Back Pain in Industry." Paper presented at the American Industrial Hygiene Association Meeting, 1974.

Brown, J.R. "Lifting as an Industrial Hazard." Am. Ind. Hyg. Assoc. J. 34:292-297, 1973.

Brown, J.R. "Manual Lifting and Related Fields: An Annotated Bibliography." Labour Safety Council of Ontario, Ontario Ministry of Labour, Ontario, Canada, 1972.

Brown, J.R. "Factors Involved in the Causation of Weight Lifting Accidents." Ergonomics. 2:117-118, 1958.

Bureau of Labor Statistics. Arkansas Workers Compensation-Supp. Data Sys. 1976.

Bureau of Labor Statistics. 1976 SDS Report for Arkansas, 1978.

Caldwell, L.S. "Body Position and the Strength and Endurance of Manual Pull." Human Factors. 6:479-483, 1964.

Caldwell, L.S.; Chaffin, D.B.; Dukes-Dobos, F.N.; Kroemer, K.H.E.; Laubach, L.L.; Snook, S.H. and Wasserman, D.E. "A Proposed Standard Procedure for Static Muscle Strength Testing." Am. Ind. Hyg. Assoc. J. 35:201-205, 1974.

Caldwell, L.S. and Grossman, E.E. "Effort Scaling of Isometric Muscle Contractions." J. Motor Behav. 5:9-16, 1973.

Caldwell, L.S. and Smith, R.P. "Subjective Estimation of Effort, Reserve and Ischemic Pain." U.S. Army Medical Research Lab. Report No. 730, Ft. Knox, Ky. 1967.

Chaffin, D.B. "A computerized Biomechanical Model: Development of and Use in Studying Gross Body Actions." J. Biomech. 2: 429-441, 1969.

Chaffin, D.B. "Some Effects of Physical Exertion." Dept. of Industrial Engineering, University of Michigan. 1972.

Chaffin, D.B. "Human Strength Capability and Low Back Pain." J. Occup. Med. 16:248-254, 1974.

Chaffin, D.B. "Manual Materials Handling and Low Back Pain." In: Occupational Medicine, Principles and Practical Applications. C. Zenz, Ed. Year Book Medical Publishers, Inc. Chicago, 1975. Chapt. 19.

Chaffin, D.B. "Ergonomics Guide for the Assessment of Human Static Strength." Am. Ind. Hyg. Assoc. J. 36:505-510,1975.

Chaffin, D.B. and Baker, W.H. "A Biomechanical Model for Analysis of Symmetric Sagittal Plane Lifting." AIIE Transactions. II(1), 1970.

Chaffin, D.B. and Moulis, E.J. "An Empirical Investigation of Low Back Strains and Vertebrae Geometry." J. Biomech. 2:89-97, 1970.

Chaffin, D.B.; Herrin, G.D.; Keyserling, W.M. and Foulke, J.A. Pre-employment Strength Testing, NIOSH Technical Report, DHEW(NIOSH) Publication No. 77-163, 1977.

Chaffin, D.B.; Herrin, G.D.; Keyserling, W.M. and Garg, A. "A Method for Evaluating the Biomechanical Stresses Resulting from Manual Materials Handling Jobs." Am. Ind. Hyg. Assoc. J. 38:662-675, 1977.

Chaffin, D.B.; Herrin, G.D. and Keyserling, W.M. "Pre-employment Strength Testing - An Updated Position." J. Occup. Med. 20: 403-408, 1978.

Chaffin, D.B. and Park, K.S. "A Longitudinal Study of Low Back Pain as Associated with Occupational Lifting Factors." Am. Ind. Hyg. Assoc. J. 34:513-525, 1973.

Christensen, E.H. "Physical Working Capacity of Old Workers and Physiological Background for Work Tests and Work Evaluations." In: Bulletin of the World Health Organization, Geneva, 1955.

Clark, A.B. and Russek, A.S. "Back Injuries." In: Rehabilitation in Industry, D.A. Covalt, Ed. Grune and Stratton, New York, 1958.

Coetsier, P. "A Psychological Study of Assemblyline Work in a Motor Vehicle Assembly Plant." Etude de Travail. 164:11-29, 1965.

Colcher, A.E. and Hursch, A.M.W. "Pre-employment Low Back X-Ray Survey: A Review of 1,500 Cases." Indust. Med. Surg. 31: 319-321, 1952.

Coleman, P.J.; Gottlief, M.S.M.; Kaplan, M.C.; Knutson, S.J.; McPeek, J.S.; Smith, K.U. and Robinson, G.H. "Human Factors Analysis of Materials Handling Equipment." Final Report, DHEW(NIOSH) Contract 210-76-0115, 1978.

Corlett, E.N. and Bishop, R.P. "A Technique for Assessing Postural Discomfort." Ergonomics. 19:175-182, 1976.

Cotes, E.N. and Meade, F. "The Energy Expenditure and Mechanical Energy Demand in Walking." Ergonomics. 3:97-119, 1960.

Cumming, G.R. "Current Levels of Fitness." Canad. Med. Assoc. J. 96:868-882, 1967.

Damon, A.; Stoudt, W.H. and McFarland, R.A. The Human Body in Experimental Design. Harvard University Press, Cambridge, 1966.

Davies, L.E. "Pacing Effects on Manned Assembly Lines." Int. J. Prod. Res. 4:69-74, 1965.

Davis, H.L.; Faulkner, T.W. and Miller, C.I. "Work Physiology." Human Factors. 11:157-166, 1969.

Davis, P.R. "Posture of the Trunk During the Lifting of Weights." Br. Med. J. 1:87-89, 1959.

Davis, P.R. and Jackson, J.M. "Manual Labour and Chronic Bronchitis." Medical Officer. 107:81-83, 1962.

Davis, P.R. and Troup, J.D.G. "Effects on the Trunk of Handling Loads in Different Postures." Proc. Second Internat. Cong. Ergonomics, Dortmund, 1964.

Davis, P.R.; Troup, J.D.G. and Burnhard, J.H. "Movements of the Thoracic and Lumbar Spine when Lifting: A Chrono-Cyclophotographic Study." J. Anat. Lond. 99:13-26, 1965.

Davis, P.R. and Stubbs, D.A. "Safe Levels of Manual Forces for Young Males (1)." Appl. Ergonomics. 8:141-150, 1977a.

Davis, P.R. and Stubbs, D.A. "Safe Levels of Manual Forces for Young Males (2)." Appl. Ergonomics. 8:219-228, 1977b.

Davis, P.R. and Stubbs, D.A. "Safe Levels of Manual Forces for Young Males (3)." Appl. Ergonomics. 9:33-37, 1978.

Dempster, W.T. "Space Requirements of the Seated Operator." WADC Technical Report 55-159. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, 1955.

Dillane, J.B.; Fry, J. and Kalton, G. "Acute Back Syndrome." Brit. Med. J. 2:82-84, 1966.

Donish, E.W. and Basmajian, J.V. "Electromyography of Deep Back Muscles in Man." Am. J. Anat. 133:25-29, 1972.

Drury, C.G. and Dawson, P. "Human Factors Limitations in Fork Lift Truck Performance." Ergonomics. 17:447-456, 1974.

Drury, C.G.; Barnes, R.E. and Daniels, E.D. "Pedestrian Operated Vehicles in Hospitals." Proc. AIIE Annual Conv., Washington, D.C., 1975.

Dryden, R.D. "A predictive Model for the Maximum Permissible Weight of Lift from Knuckle to Shoulder Height." PhD Dissertation, Texas Tech University, 1973.

Dukes-Dobos, F.N. "Rationale and Provisions of the Work Practices Standard for Work in Hot Environments as recommended by NIOSH." In: Standards for Occupational Exposures to Hot Environments, M.S. Horvath and R.C. Jensen, Eds. DHEW(NIOSH) Publication No. 76-100, 1976.

Durnin, J.V.G.A. and Passmore, R. Energy, Work and Leisure. Heineman Educational Books, London, 1967.

Edholm, O.G. The Biology of Work. McGraw Hill, New York, 1967.

Eisler, H. "Subjective Scale of Force for a Large Muscle Group." J. Exper. Psych. 63:253-257, 1962.

Ekblom, B.; Astrand, P.O.; Saltin, B.; Stenberg, J. and Wallstrom, B. "Effects of Training on Circulatory Response to Exercise." J. Appl. Physiol. 24:518-527, 1968.

El-Bassoussi, M.M. "A Biomechanical Dynamic Model for Lifting in the Sagittal Plane." PhD Dissertation, Texas Tech University, 1974.

Emanuel, I.; Chafee, J. and Wing, J. "A Study of Human Weight Lifting Capabilities for Loading Ammunition into the F-86 Aircraft." U. S. Air Force (WADC-TR 056-367), 1956.

Evans, F.G. and Lissner, H.R. "Biomechanical Studies on the Lumbar Spine and Pelvis." J. Bone Joint Surg. 41A:218-290, 1959.

Evans, W.O. "A Titration Schedule on a Treadmill." U.S. Army Medical Research Laboratory, Report No. 525, Ft. Knox, Ky, 1961.

Evans, W.O. "The Effect of Treadmill Grade on Performance Decrement Using a Titration Schedule." U.S. Army Medical Research Laboratory, Report No. 535, Ft. Knox, Ky., 1962.

Farfan, H.F. "The Effects of Torsion on the Lumbar Intervertebral Joints: The Role of Torsion in the Production of Disc Degeneration. J. Bone Joint Surg. 52A:468-483,1970.

Fiorini, G.T. and McCommond, D. "Forces on the Lumbo-Vertebral Facets." Ann. Biomed. Eng. 4:354-363, 1976.

Fitzgerald, J.G. "Changes in Spinal Stature Following Brief Periods of Shoulder Loading." Royal Air Force Institute of Aviation Medicine, IAM Report No. 514, 1972.

Floyd, W.F. "Physiological Factors Concerned with Weight Lifting." Ergonomics Res. Soc. Proc. London School of Hygiene and Tropical Medicine, 1958.

Fox, J.G. "Research on the Ergonomics of Fork Lift Trucks." Paper presented at Conference on Human Factors in Materials Handling. Ergonomics Research Society, London, 1971.

Frederick, W.S. "Human Energy in Manual Lifting." Modern Materials Handling. March, 1959.

Garg, A. "A Metabolic Rate Prediction Model for Manual Materials Handling Jobs." PhD Dissertation, University of Michigan, 1976.

Garg, A. and Chaffin, D.B. "A Biomechanical Computerized Simulation of Human Strength." AIIE Transactions. 7:1-15, 1975.

Garg, A.; Chaffin, D.B. and Herrin, G.D. "Prediction of Metabolic Rates for Manual Materials Handling Jobs." Am. Ind. Hyg. Assoc. J. 39:661-674, 1978.

Garg, A. and Saxena, U. "Effects of Lifting Frequency and Techniques on Physical Fatigue with Special Reference to Psychophysical Methodology and Metabolic Rate." Am. Ind. Hyg. Assoc. J. 40:894-903, 1979.

Garrett, J.W. "The Adult Human Hand: Some Anthropometric and Biomechanical Considerations." Human Factors. 13:117-131, 1971.

Garry, R.C.; Passmore, R.; Warnock, G.M. and Durnin, J.V.G.A. "Expenditure of Energy and the Consumption of Food by Miners and Clerks." Med. Res. Council Spec. Rep. Ser. 289, Her Majesty's Stat. Off., 1955.

Gimlett, D.M. "The Back X-Ray Controversy." J. Occup. Med. 14: 785-786, 1972.

Givoni, B. and Goldman, R.F. "Predicting Metabolic Energy Cost." J. Appl. Physiol. 30:429-433, 1971.

Givoni, B. and Goldman, R.F. "Predicting Heart Rate Response to Work, Environment and Clothing." J. Appl. Physiol. 34:201-204, 1973.

Grandjean, E. Fitting the Task to the Man. Taylor and Francis, Ltd., London, 1969.

Grimby, G. and Soderholm, B. "Energy Expenditure of Men in Different Age Groups During Level Walking and Bicycle Ergometry." Scand. J. Clin. Lab. Invest. 14:321-328, 1962.

Grinnold, R.E. "A Follow-Up Study of Permanent Disability under Wisconsin Worker's Compensation." PhD Dissertation, University of Wisconsin, 1976.

Hamilton, B.J. and Chase, R.B. "A Work Physiology Study of the Relative Effects of Pace and Weight in a Carton Handling Task." AIIE Transactions. 1:106-111, 1969.

Hanman, B. "The Evaluation of Physical Ability." New. Eng. J. Med. 258:986-993, 1958.

Harley, W.J. "Lost Time Back Injuries: Their Relationship to Heavy Work and Preplacement Back X-Rays." J. Occup. Med. 14:511-614, 1972.

Harper, F.C.; Warlow, W.J. and Clarke, B.L. "The Forces Applied to the Floor by the Foot in Walking." National Building Studies Research Paper 32. Her Majesty's Stat. Off., 1961.

Herndon, R.F. "Back Injuries in Industrial Employees." J. Bone Joint Surg. 9:234-269, 1927.

Herrin, G.D.; Chaffin, D.B. and Mach, R.S. "Criteria for Research on the Hazards of Manual Materials Handling." NIOSH Contract Report, CDC 99-74-118, 1974.

Hill, A.V. "The Heat of Shortening and the Dynamic Constants of Muscle." Proc. Roy. Soc. London. B126:136-195, 1938.

Himberry, S. "Kinetic Methods of Manual Handling in Industry." Occup. Safety Health Series, International Labour Organization, No. 10, 1967.

Hirabayashi, I.; Ikeda, K.; Tsuchihashi, Z; Morita, T. and Saito, M. "Spondylolysis and Spondylolisthesis: Pathological Conditions and Therapeutic Indications." J. Jap. Orthop. Assoc. 46:49-68, 1972.

Hirsch, T. "The Billion Dollar Backache." Nat. Safety News. May, 1977.

Hirschfield, A.H. and Behan, R.C. "The Accident Process. I. Etiological Consideration of Industrial Injuries." J. Am. Med. Assoc. 186:193-199, 1963.

Houghton, F.C. and Yagloglou, C.P. "Determination of the Comfort Zone." J. Am. Soc. Heating Ventil. Eng. 29:515-536, 1923.

Houston, C.S. "Pre-employment Radiographs of Lumbar Spine." J. Canad. Assoc. Radiol. 28:170, 1977.

Hult, L. "Cervical, Dorsal and Lumbar Spinal Syndromes." Acta Orthop. Scand. Suppl. 17, 1954.

International Labour Organization. "Manual Lifting and Carrying." Int. Occup. Safety Health Infor. Sheet #3, Geneva, 1962.

International Labour Organization. "Maximum Permissible Weight to Be Carried by One Worker." ILO Office, Geneva, 1964-1967.

Irvine, C.W. "A New Slipmeter for Evaluating Slippery Walkways." Materials Research Standards. 7:535-542, 1967.

Jackson, A.; Kirwan, E.O.G. and Sullivan, M.F. "Pathogenesis and Treatment of Lytic Spondylolisthesis at the L 4/5 Level." Paper presented at the International Society for the Study of the Lumbar Spine, Utrecht, 1977.

Jones, D.F. "Back Strains: The State of the Art." J. Safety Res. 3:38-41, 1971.

Jorgenson, K. and Poulson, E. "Physiological Problems in Repetitive Lifting with Special Reference to Tolerance Limits to the Maximum Lifting Frequency." Ergonomics. 17:31-40, 1974.

Kamon, E. and Belding, H.S. "The Physiological Cost of Carrying Loads in Temperate and Hot Environments." Human Factors. 13:153-161, 1971.

Kamon, E. and Goldfuss, A.J. "In-Plant Evaluation of the Muscle Strength of Workers." Am. Ind. Hyg. Assoc. J. 39:801-807, 1978.

Kazarian, L.E. "Dynamic Response Characteristics of the Human Vertebral Column." Acta. Orthop. Scand. Suppl. 146, 1972.

Kazarian, L.E. "Creep Characteristics of the Human Spinal Column." Orthop. Clin. N. Amer. 6:3-18, 1975.

Kazarian, L.E. "Standardization and Interpretation of Spinal Injury Criteria." Aerospace Med. Res. Lab. Tech. Review, AMRL-TR-75-85. Wright Patterson Air Force Base, Ohio, 1978.

Kazarian, L.E. and Graves, G.A. "Compressive Strength Characteristics of the Human Vertebral Centrum." Spine. 2:1-14, 1977.

Kellermann, F.T. and vanWely, P.A. "The Optimum Size and Shape of Container for Use by the Flower Bulb Industry." Ergonomics. 4:219-228, 1961.

Kelly, F.J. "Evaluating Musculoskeletal Capabilities- A Practical Approach." J. Occup. Med. 17:266-269, 1975.

Keyserling, W.M.; Herrin, G.D. and Chaffin, D.B. "An Analysis of Selected Work Muscle Strength." Proceedings of the Human Factors Society 22nd Annual Meeting, Detroit, 1978.

Khalil, T.M. "An Electromyographic Methodology for the Evaluation of Industrial Design." Human Factors. 15:257-264, 1973.

Knipfer, R.E. "Predictive Models for the Maximum Acceptable Weight of Lift." PhD Dissertation, Texas Tech University, 1974.

Konz, S.; Dey, S. and Bennett. C. "Forces and Torques in Lifting." Human Factors. 15:237-245, 1973.

Kosiak, M.; Aurelius, J.R. and Harfield, W.F. "Backache in Industry." J. Occup. Med. 8:51-58, 1966.

Koyl, L.F. and Hanson, P.M. "Age, Physical Ability and Work Potential." National Council on Aging, U.S. Manpower Administration and U.S. Department of Labor, 1969.

Kraus, H. "Prevention of Low Back Pain." J. Occup. Med. 9:555-559, 1967.

Kroemer, K.H.E. "Push Forces Exerted in 65 Common Working Positions." Aerospace Med. Res. Lab. Tech. Report, AMRL-TR-68-143, Wright Patterson Air Force Base, Ohio, 1969.

Kroemer, K.H.E. "Human Strength Terminology, Measurement and Interpretation of Data." Human Factors. 12:297-313, 1970.

Kroemer, K.H.E. "Foot Operation of Controls: Speed of Activation and Exertion of Force to Pedals, Perception, Speed and Accuracy of Leg and Foot Motion." Ergonomics. 14:333-361, 1971.

Kroemer, K.H.E. and Howard, J.M. "Towards Standardization of Muscle Strength Testing." Med. Sci. Sports. 2;224, 1970.

Kroemer, K.H.E. "Horizontal Push and Pull Forces." Appl. Ergonomics. 5:94-102, 1974.

Lamy, C. "Hydraulic Behavior of Vertebral Body." Paper presented at the International Society for the Study of the Lumbar Spine, San Francisco, 1978.

LaRocca, H. and MacNab, I. "Value of Pre-employment Radiographic Assessment of the Lumbar Spine." Canad. Med. Assoc. J. 101:383-388, 1969.

Laubach, L.L. "Comparative Muscular Strength of Men and Women: A Review of the Literature." Aviat. Space Environ. Med. 47: 534-542, 1976.

Laubach, L.L.; Kroemer, K.H.E. and Thordsen, M.L. "Relationships Among Isometric Forces Measured in Aircraft Control Locations." Aerospace Med. 43:738-742, 1972.

Laubach, L.L. and McConville, J.T. "The Relationship of Strength to Body Size and Typology." Med. Sci. Sports. 1:189-194, 1969.

Lawrence, J.S. "Disc Degeneration: Its Frequency and Relationship to Symptoms." Ann. Rhum. Dis. 28:121-138, 1969.

Lehmann, G. Praktische Arbeitsphysiologie. Verlag, Stuttgart, 1953.

Lind, A.R.; McNicol, G.W. and Donald, K.W. "Circulatory Adjustments to Sustained (Static) Muscular Activity." Proceedings, Symposium Physical Activity in Health and Disease, Universitetsforlaget, Oslo, 1966.

Lind, A.R. and McNicol, G.W. "The Cardiovascular Responses to Holding and Carrying Weights by Hand and by Shoulder Harness," with Special Reference to Stretcher Carrying." J. Appl. Physiol. 25:261-267, 1968.

Lind, A.R.; Petrofsky, J.S. and Betz, W. "A Comparative Study of Metabolic, Respiratory and Cardiovascular Characteristics of Fatigue During Lifting Tasks and Bicycle Ergometry." Final Report, DHEW(NIOSH) Contract CDC 00-74-8., 1977.

Lind, A.R.; Williams, C.A. and Petrofsky, J.S. "Physiological Responses of Women to Repetitive Lifting and an Examination of Factors Responsible for Fatigue." Final Report, DHEW(NIOSH) Contract 210-77-0044, 1979.

Lovestead, G.E. "Top 10 Fork Lift Accidents." Nat. Safety News. 16:123-127, 1977.

McCall, I.W.; O'Brien, J.P. and Park, W.M. "Induced Pain Referal from Posterior Lumbar Elements in Normal Subjects." Paper presented at the International Society for the Study of the Lumbar Spine, San Francisco, 1978.

McConville, J.T. and Hertzberg, H.T.E. "A Study of One-Handed Lifting." Aerospace Med. Res. Lab. Tech. Report AMRL-TR-66-17, Wright Patterson Air Force Base, Ohio, 1966.

McConville, J.T. and Hertzberg, H.T.E. "A Study of One-Handed Lifting: A Final Report." Ergonomics. 11:297-304, 1968.

McCormick, E.J. Human Factors in Engineering and Design. 4th Ed. McGraw Hill, New York, 1976.

McDaniel, J.W. "Prediction of Acceptable Lift Capability." PhD Dissertation, Texas Tech University, 1972.

McGill, C.M. "Industrial Back Problems: A Control Program." J. Occup. Med. 10:174-176, 1968.

Magnuson, P.B. and Coulter, J.S. "Workmen's Backache." Int. Clin. 31:214-253, 1921.

Magora, A. "An Investigation of the Problem of Sick Leave in the Patient Suffering from Low Back Pain." Ind. Med. Surg. 38: 398-408, 1969.

Magora, A. "Investigation of the Relation between Low Back Pain and Occupation. Part I." Ind. Med. Surg. 39:21-37, Nov. 1970.

Magora, A. "Investigation of the Relation between Low Back Pain and Occupation. Part II." Ind. Med. Surg. 39:28-34, Dec. 1970.

Magora, A. "Investigation of the Relation between Low Back Pain and Occupation. Part 6. Scand. J. Rehab. Med. 6:81-88, 1974.

Magora, A. and Schartz, A. "Relation between the Low Back Pain Syndrome and X-Ray Findings. 1. Degenerative Arthritis." Scand. J. Rehab. Med. 8:115-125, 1976.

Manning, D.P. "Industrial Accident-Type Classifications: A Study of the Theory and Practice of Accident Prevention Based on a Computer Analysis of Industrial Injury Records." MD Thesis, University of Liverpool, 1971.

Marshall, L.L.; Trethewie, E.R. and Curtain, C.C. "Chemical Radiculitis: A Clinical, Physiological and Immunological Study." Clin. Orthop. 129:61-67, 1977.

Martin, J.B. and Chaffin, D.B. "Biomechanical Computerized Simulation of Human Strength in Sagittal Plane Activities." AIIE Transactions. 4:19, 1972.

Mertens, H. "Nonlinear Behavior of Sitting Human under Increasing Gravity." Aviat. Space Environ. Med. 49:287-298, 1978.

Miller, J.C.; Farlow, D.E. and Seltzer, M.L. "Physiological Analysis of Repetitive Lifting." Aviat. Space Environ. Med. 48:984-988, 1977.

Miner, M.G. and Miner, J.B. Employee Selection within the Law. Bureau of National Affairs, Inc., Washington, D.C. 1978.

Mital, A.; Ayoub, M.M.; Asfour, S.S. and Bethea, N.J. "Relationship between Lifting Capacity and Injuries in Occupations Requiring Lifting." Proceedings of the Human Factors Society 22nd Annual Meeting, Detroit, 1978.

Montgomery, C.H. "Pre-employment Back X-Rays." J. Occup. Med. 18:495-498, 1976.

Mooney, V. and Robertson, J. "The Facet Syndrome." Clin. Orthop. 115:149-156, 1976.

Moores, B. "A Comparison of Work Load Using Physiological and Time Assessment." Ergonomics. 14:61-69, 1970.

Moreton, R.D. "The Role of Preplacement Roentgen Examination in Evaluation of Low Back Pain." South. Med. J. 67:1105-1110, 1974.

Moreton, R.D.; Winston, J.R. and Bibby, D.E. "Value of Preplacement Examination of the Lumbar Spine." Radiology. 70:661-665, 1958.

Morris, J.M.; Lucas, D.B. and Bresler, B. "Role of the Trunk in Stability of the Spine." J. Bone Joint Surg. 43A:327-351, 1961.

Munchinger, R. "Manual Lifting." International Labour Organization, Geneva, 1962.

Murphy, R.W. "Nerve Roots and Spinal Nerves in Degenerative Disc Disease." Clin. Orthop. 129:46-60, 1977.

Murrell, K.F.H "Man in His Working Environment." In: Ergonomics. Chapman and Hall, London, 1969.

Nachemson, A. "Low Back Pain, Its Etiology and Treatment." Clin. Med. 78:18-24, 1971.

Nachemson, A. and Elfstrom, G. Intravital Dynamic Pressure Measurements in Lumbar Discs. Almqvist and Wiksell, Stockholm, 1970.

Napier, S. "The Prehensile Movements of the Human Hand." J. Bone Joint Surg. 38B:902-913, 1956.

National Safety Council. Accident Facts. 1975.

Nordgren, B. "Athropometric Measures and Muscle Strength in Young Women." Scand. J. Rehab. Med. 4:165-169, 1972.

Park, K.S. "A Computerized Simulation Model of Postures During Manual Materials Handling." PhD Dissertation, University of Michigan, 1973.

Parvi, V and Virolainen, M. "Roentgenographic Findings of the Lumbosacral Spine in Preemployment Examination of Lumbermen with Special Reference to Spondylolisthesis." Scand. J.Work Environ. Health. 1:40-44, 1975.

Perey, O. "Fracture of the Vertebral End-Plate in the Lumbar Spine: An Experimental Biomechanical Investigation." *Acta Orthop. Scand*. Suppl. 25, 1957.

Petrofsky, J.S. and Lind, A.R. "Aging, Isometric Strength, Endurance and Cardiovascular Response to Static Effort." *J. Appl. Physiol*. 38:91-95, 1975.

Petrofsky, J.S. and Lind, A.R. "Metabolic, Cardiovascular and Respiratory Factors in the Development of Fatigue in Lifting Tasks." *J. Appl. Physiol.: Respirat. Environ. Exercise Physiol*. 45:64-68, 1978.

Petrofsky, J.S. and Lind, A.R. "Comparison of Metabolic and Ventilatory Responses of Men to Various Lifting Tasks and Bicycle Ergometry." *J. Appl. Physiol.: Respirat. Environ. Exercise Physiol*. 45:60-63, 1978a.

Pfauth, M.J. and Miller, J.M. "Work Surface Friction Coefficients: A Survey of Relevant Factors and Measurement Methodology." *J. Safety Res*. 8:77-90, 1976.

Pheasant, S. and O'Neill D. "Performance in Gripping and Turning: A Study in Hand/Handle Effectiveness." *Appl. Ergonomics*. 6:205-208, 1975.

Pollock, M.L.; Miller, H.S. Jr.; Janeway, R.; Linnerud, A.C.; Robertson, B. and Valentino, R. "Effects of Walking on Body Composition and Cardiovascular Function in Middle-Age Men." *J. Appl. Physiol*. 30:126-130, 1971.

Porter, R.W.; Hibbert, C. and Wellman, P. "Backache and the Lumbar Spine Canal." *Spine*. 5:99-105, 1980.

Poulson, E. and Jorgenson, K. "Back Muscle Strength, Lifting and Stoop Working Postures." *Appl. Ergonomics*. 1:133-137, 1971.

Powell, P.J.; Hale, J.; Martin, J and Simon, M. "2,000 Accidents: A Shop Floor Study of Their Causes Based on 42 Months' Continuous Observation. App.17." *Ergonomics of Good Handling*, National Institute of Industrial Psychology, London, 1971. pp 106-108.

Rais, O. "Heparin Treatment of Peritenomyosis (peritendinitis) Crepitans Acuta: A Clinical and Experimental Study Including the Morphological Chenges in Peritenon and Muscles." *Acta Chir. Scand*. Suppl. 268, 1961.

Redfield, J.T. "The Low Back X-Ray as a Pre-employment Screening Tool in the Forest Products Industry." *J. Occup. Med*. 13:219-226, 1971.

Rigby, L.V. "Why Do People Drop Things?" Quality Progress. 16-19, Sept. 1973.

Rodahl, K. and Issekutz, B. "Physical Performance Capacity in the Older Individual." In: Muscle as a Tissue. McGraw-Hill, New York, 1962. Chapt. 14.

Rodgers, S.H. "Metabolic Indices in Materials Handling Tasks." In: Safety in Manual Materials Handling. C.G. Drury, Ed. DHEW(NIOSH) Publication No. 78-185, 1978. pp 52-56.

Roebuck, J.A.; Kroemer, K.H.E. and Thompson, W.G. Engineering Anthropometry Methods. John Wiley and Sons,Inc.,New York, 1975.

Rolander, S.D. " Motion of the Lumbar Spine with Special Reference to the Stabilizing Effect of Posterior Fusion: An Experimental Study on Autopsy Specimens." Acta Orthop. Scand. Suppl. 90, 1966.

Ronnholm, H.; Harvonen, M.J. and Lapinleimu, V.O. "Physiological Studies in the Optimum Rhythm of Lifting Work." Ergonomics. 5:52-53, 1962.

Rowe, M.L. "Low Back Pain in Industry: A Position Paper." J. Occup. Med. 11:161-169, 1969.

Rowe, M.L. "Low Back Pain: Updated Position." J. Occup. Med. 13:476-478, 1971.

Saari, J. and Wickstrom, G. "Load on Back in Concrete Reinforcement Work." Scand. J. Work Environ. Health. Suppl. 1: 13-19, 1978.

Safety in Manual Materials Handling. C.G. Drury, Ed. DHEW(NIOSH) Publication No. 78-185, 1978.

Safety Sciences, Inc. "Collection and Analysis of Work Surface Accident Profile Data." Draft Final Report, DHEW(NIOSH) Contract 210-76-0150, 1977.

Salvaterra, P. and Chiusano, R. "Optimum Cylindrical Handles." Unpublished Report. Industrial Engineering Dept. State University of New York(Buffalo), 1977.

Sanderson, C.W. "A Study on Handle Design." Unpublished Report. State University of New York(Buffalo), 1976.

Saran, C. "Biomechanical Evaluation of T-handles for a Pronation-Supination Task." J. Occup. Med. 15:712-716, 1973.

Sell, R.G. "Ergonomics as Applied to Crane Cabs." In: Human Factors in Work, Design and Production. Taylor and Francis, Ltd., London, 1977. pp 1-43.

Sigler, P.A. "Relative Slipperiness of Floor and Deck Surfaces." Building Materials and Structures Report. National Bureau of Standards, BMS, 100, July, 1943.

Smith, L.E. and Edwards, D.K. "Prediction of Muscular Endurance from Individual Differences in Initial and Post Training Increments from Static Strength." Human Factors. 10:345-350, 1968.

Snook, S.H. "Group Work Capacity: A Technique for Evaluating Physical Tasks in Terms of Fatigue." Unpublished Report, Liberty Mutual Ins. Co., Boston, 1965.

Snook, S.H. "The Effects of Age and Physique on Continuous Work Capacity." Human Factors. 13:467-479, 1971.

Snook, S.H. "Psychophysiological Indices-What People Will Do." In: Safety in Manual Materials Handling. C.G. Drury, Ed. DHEW(NIOSH) Publication No. 78-185, 1978. pp 63-67.

Snook, S.H. "The Design of Manual Handling Tasks." Ergonomics Society Lecture given at the Cranfield Institute of Technology, Bedfordshire, England, 1978.

Snook, S.H. "The Design of Manual Handling Tasks." Ergonomics. 21:963-985, 1978.

Snook, S.H. and Ciriello, V.M. "The Effects of Heat Stress on Manual Handling Tasks." Am. Ind. Hyg. Assoc. J. 35:681-685, 1974a.

Snook, S.H. and Ciriello, V.M. "Maximum Weights and Work Loads Acceptable to Female Workers." J.Occup. Med. 16:527-534, 1974b.

Snook, S.H. and Irvine, C.H. "Maximum Acceptable Weight of Lift." Am. Ind. Hyg. Assoc. J. 28:322-329, 1967.

Snook, S.H. and Irvine, C.H. "Maximum Frequency of Lift Acceptable to Male Industrial Workers." Am. Ind. Hyg. Assoc. J. 29:531-536, 1968.

Snook, S.H. and Irvine, C.H. "Psychophysical Studies of Physiological Fatigue Criteria." Human Factors. 11:291-300, 1969.

Snook, S.H.; Irvine, C.H. and Bass, S.F. "Maximum Weights and Workloads Acceptable to Male Industrial Workers." Am. Ind. Hyg. Assoc. J. 31:579-586, 1970.

Sonoda, T. "Studies on the Compression, Tension, and Torsion Strength of the Human Vertebral Column." J. Kyoto Prefect Med. Univ. 71:659-702, 1962.

Soule, R.G. and Goldman, R.F. "Energy Cost of Load Carried on the Head, Hands or Feet." J. Appl. Physiol. 27:687-690, 1969.

Stevens, J.C. and Cain, W.S. "Effort in Muscular Contractions Related to Force Level and Duration." Perception Psychophysics. 8:240-244, 1970.

Stevens, S.S. "The Direct Estimation of Sensory Magnitudes-Loudness." Am. J. Psych. 69:1-25, 1956.

Stevens, S.S. "The Psychophysics of Sensory Function." Am. Sci. 48:226-253, 1960.

Stevens, S.S. Psychophysics-Introduction to its Perceptual, Neural and Social Prospects. John Wiley and Sons, Inc., New York, 1975.

Stewart, S.F. "Pre-employment Examination of the Back." J. Bone Joint Surg. 29:215-221, 1947.

Strindberg, L. and Peterson, N.F. "Measurement of Force Perception in Pushing Trolleys." Ergonomics. 15:435-438, 1972.

Sury, R.J. "The Stimulation of a Paced Single-State Work Task." Int. J. Prod. Res. 4:125-140, 1965.

Switzer, S.A. "Weight-Lifting Capabilities of a Selected Sample of Human Males." Aerospace Med. Res. Lab. , Report No. AD-284054, Wright Patterson Air Force Base, Ohio, 1962.

Tauber, J. "An unorthodox Look at Backache." J. Occup. Med. 12: 128-130, 1970.

Taugher, N.J. "Back Injuries." Technical Report, State of Wisconsin, Dept. of Industry, Labor and Human Relations, 1973.

Thordsen, M.L.; Kroemer, K.H.E. and Laubach, L.L. "Human Forces Exertions in Aircraft Control Locations." Aerospace Med. Res. Lab. Tech. Report, AMRL-TR-71-119, Wright Patterson Air Force Base, Ohio, 1972.

Tichauer, E.R. "Some Aspects of Stress on Forearm and Hand in Industry." J. Occup. Med. 8:63-71, 1966.

Tichauer, E.R. "A Pilot Study of the Biomechanics of Lifting in Simulated Industrial Situations." J. Safety Res. 3:98-115, 1971.

Tichauer, E.R. "Ergonomic Aspects of Biomechanics." In: The Industrial Environment: Its Evaluation and Control. USDHEW/ PHS/CDC/NIOSH, 1973.

Tichauer, E.R. The Biomechanical Basis of Ergonomics. John Wiley and Sons, Inc., 1978.

Tichauer, E.R.; Miller, G. and Nathan, I. "Lordosimetry: A New Technique for the Measurement of Postural Response to Materials Handling." Am. Ind. Hyg. Assoc. J. 34:1-12, 1973.

Tilley, P. "Is Sacralization a Significant Factor in Lumbar Pain?" J. Am. Osteop. Assoc. 70:238-241, 1970.

Troup, J.D.G. "Mechanical Factors in Spondylolisthesis and Spondyolysis." Clin. Orthop. 117:59-67, 1976.

Troup, J.D.G. and Chapman, A.E. "The Static Strength of the Lumbar Erectores Spinae." J. Anat. 105:186, 1968.

Troup, J.D.G. and Chapman, A.E. "The Strength of the Flexor and Extensor Muscles of the Trunk." J. Biomech. 2:49-62, 1969.

Troup, J.D.G.; Roantree, W. V. and Archibald, R.M. "Survey of Cases of Lumbar Spine Disability: A Methodological Study." Medical Officers Broadsheet. National Coal Board, Feb. 1970.

Troup, J.D.G.; Hodgson, S.; Shannon, H.S. and Chapman, M. "Lumbar Spinal Radiology in an Epidemiological Survey of 326 Dock Workers." Unpublished Data, 1974.

U.S. Department of Labor. "Teach Them to Lift." Safety in Industry Series. Bull. 110, Wage and Standards Admin. , Bureau of Labor Standards, Revised, 1970.

U.S. Department of Labor. Handbook of Labor Statistics. 1977.

VanCott, H.P. and Kincade, R.G. Human Engineering Guide to Equipment Design. U.S. Government Printing Office, Washington, D.C., 1972. Revised Edition.

VanderWalt, W.H. and Wyndham, C.H. "An Equation for Prediction of Energy Expenditure of Walking and Running." J. Appl. Physiol. 34:559-563, 1973.

Voorlichtingsbureau voor de Voeding. "Nederlandse Voedingsmiddelentabel." Voeding. 19:63, 1958.

Westrin, C.G. "Low Back Sick-Listing: A Nosological and Medical Insurance Investigation." Scand. J. Soc. Med. Suppl. 7, 1973.

White, W.M. "The Compensation Back." Appl. Therap. 8:871-874, 1973.

Whitney, R.J. "The Strength of the Lifting Action in Man." Ergonomics. 1:101-128, 1958.

Wickstrom, G.; Nanninen, K.; Lahtinen, M. and Riihimaki, H. "Previous Back Syndromes and Present Back Symptoms in Concrete Reinforcement Workers." Scand. J. Work Environ. Health. 4, Suppl. 1:20-28, 1978.

Wilkins, G.F.; Schilling, J.W. and Showalter, E.J. "Industrial Back Injuries-Bell System." Am. Med. Assoc. Arch. Ind. Health. 15:91-100, 1957.

Williams, C.A.; Petrofsky, J.S. and Lind, A.R. "Physiological Responses of Women During Lifting Exercise." Submitted for publication to the Eur. J. Appl. Physiol., 1980.

Wiltse, L.L.; Newman, P.H. and McNab, I. "Classification of Spondylolysis and Spondylolisthesis." Clin. Orthop.117: 23-29, 1976.

Wisconsin Bureau of Research and Statistics. Work Force 1980, Occupational Projections. Wisconsin Department of Industry, Labor and Human Relations, 1974.

Women's Bureau. 1975 Handbook on Women Workers. Employment Standards Administration, U.S. Department of Labor, Bull. 297, 1975.

Workmen's Compensation Division, Department of Industry, Labor and Human Relations, State of Wisconsin, Workmen's Compensation Statistics, 1978.

Woodson, W. "Good Human Engineering Is Possible Using off the Shelf Component Products." Human Factors. 13:141-152, 1971.

Wyke, B. "Neurological Aspects of Low Back Pain." In: The Lumbar Spine and Back Pain. M.I.V. Jayson, Ed. Sector Publishing Co., London, 1976. pp 189-256.

APPENDIX

This appendix contains a sensitivity analysis of the work practice guide equation presented in Chapter 8. For a variety of vertical and horizontal hand locations, vertical travel distances, and frequencies of lifting, the action limit (AL) and maximum permissible limit (MPL) are evaluated in terms of:

1. the expected percent of the workforce capable based on dynamic strength, Ayoub, et al., (1978) and Snook (1978),
2. the range of expected percent of the workforce capable based on isometric strength, Chaffin, et al., (1978),
3. the lower and upper bounds on predicted static compressive force at the L_5/S_1 vertebral level, Chaffin, et al., (1978), and
4. the range of predicted metabolic rates according to Garg, et al., (1978).

In all cases, the AL is evaluated based upon a female industrial population; the MPL is based upon a male industrial population.

Ranges for the last three indices were obtained by calculating these values for both the least- and most-desirable posture. For example, the metabolic expenditure for low lifting in a squat posture is greater than when lifting in a stoop posture (see Chapter 4). Therefore, the value corresponding to the squat posture is least preferred and represents the upper bound on metabolic rate. The lower value corresponds to a stoop posture. No range is given when the vertical hand location is 81 cm or higher because it is assumed that only a stand posture would be appropriate for lifting. A detailed explanation of the derivation of values for each column follows.

DYNAMIC % CAPABLE

The table value is calculated by obtaining the standard normal distribution Z-value for the given vertical and horizontal hand location, travel distance and frequency suggested in Chapter 5 (Table 5.7). For the Action Limit (Table A.1) the ranges assumed were as follows:

floor to knuckle: 15 cm and 50 cm vertical
knuckle to shoulder: 75 cm and 125 cm vertical
shoulder to reach: 150 cm and 175 cm

A horizontal hand location (in the sagittal plane) of 46 cm is assumed. The complementary cumulative probability of the standard normal distribution is recorded in the table as the expected percent capable for the given set of conditions. The values in Table 5.7 for males were, likewise, used to obtain the percent capable for the MPL in Table A.2.

ISOMETRIC % CAPABLE

The table value is obtained by entering the vertical and horizontal hand locations and the AL into the biomechanical model reported by Chaffin, et al., (1978). The following postures were also assumed:

deep squat, squat or stoop: 15 cm and 50 cm vertical
squat or stoop: 75 cm vertical
stand: 125 cm, 150 cm and 175 cm vertical

The minimum and maximum female percent capable for the various postures are entered in Table A.1. Lateral hand separation was assumed to be 20 cm. It should also be noted that this biomechanical model assumes average male and female anthropometric dimensions. The same procedure was used for the MPL (Table A.2) but values represent the percent of the male workforce capable.

BACK COMPRESSION

Tables A.1 and A.2 present upper and lower bounds on static back compressive force obtained with the same input to the biomechanical model used for (isometric % capable) above. The larger value is the maximum back compression obtained for the various postures and the lower value is the minimum back compression for the given set of conditions.

Once again, the upper and lower bounds on back compression for the AL represent biomechanical model output for the female working population (Table A.1) and bounds for the MPL (Table A.2) represent male back compression estimates. Preferred and least desirable postures are not necessarily the same for males versus females or strength versus back compression.

METABOLIC RATE

The Garg, et al., (1978) equation presented in Chapter 4 was used in the estimation of the expected metabolic rate (Kcal/min.). Female 50 percentile body weight was used when calculating the rate corresponding to the AL, and 50 percentile male body weight for the rate corresponding to the MPL. Also, basal metabolic rate for a bent standing posture was assumed when the vertical hand position was 81 cm or less (irrespective of the travel distance), whereas the basal rate for a standing posture was used otherwise (i.e., 82 cm and above). The lower value corresponds to an assumed stoop lift and the larger value assumes a squat lift. Obviously, such a range can only be calculated when the lift begins below 81 cm. Above 81 cm, the equation for an arm lift was used to calculate the metabolic expenditure per lift.

For frequencies of .2 lifts per minute, the metabolic rates represent basal metabolic rates. Horizontal hand location is not accounted for in these estimates.

Table A.1: Action Limit Sensitivity Analysis

V (cm) VERT	H (cm) HORZ	D (cm) DIST	F (per min)	ACTION LIMIT (AL)	DYNAM % CAP	ISOMETRIC % CAPABLE		BACK COMPRESS.		MET. RATE	
						LOWER	UPPER	LOWER	UPPER	LOWER	UPPER
15	15	25	<.2	30	---	82	92	154	316	1.8	1.8
			1	28	---	85	94	149	297	2.0	2.2
			10	5	---	---	---	111	146	3.3	4.2
15	15	75	<.2	24	---	88	96	143	273	1 8	1.8
			1	22	---	90	97	140	260	2.2	2.4
			10	4	---	---	---	110	142	3.7	4.7
15	45	25	.2	10	---	87	90	246	271	1.8	1.8
			1	9	98	89	92	239	262	2.0	2.1
			10	2	99	---	---	162	191	3.2	4.0
15	45	75	<.2	8	---	91	93	231	254	1.8	1.8
			1	7	99	92	94	224	245	2.0	2.2
			10	1	99	---	---	156	186	3.3	4.2
15	75	25	<.2	6	---	39	75	284	367	1.8	1.8
			1	6	---	42	77	278	360	2.0	2.1
			10	1	---	---	---	215	278	3.2	4.0
15	75	75	<.2	5	---	45	80	272	352	1.8	1.8
			1	4	---	48	88	265	342	2.0	2.1
			10	1	---	---	---	215	278	3.3	4.1
50	15	25	<.2	36	---	56	97	317	375	1.8	1.8
			1	33	---	66	97	305	362	2.0	2.1
			10	6	---	---	---	163	232	2.7	3.2
50	15	74	<.2	29	---	81	98	286	340	1.8	1.8
			1	26	---	87	99	276	330	2.3	2.4
			10	5	---	---	---	157	228	3.4	3.9
50	45	25	.2	12	---	88	96	295	362	1.8	1.8
			1	11	93	90	97	283	348	1.9	2.0
			10	2	99	---	---	166	243	2.5	2.9
50	45	75	<.2	10	---	94	97	265	326	1.8	1.8
			1	9	99	95	98	254	316	2.0	2.1
			10	2	99	---	---	166	243	2.9	3.3
50	75	25	<.2	7	---	71	80	349	374	1.8	1.8
			1	7	---	74	82	342	365	1.9	2.0
			10	1	---	---	---	262	268	2.5	2.9
50	75	75	<.2	6	---	80	87	329	349	1.8	1.8
			1	5	---	83	89	322	341	2.0	2.0
			10	1	---	---	---	255	260	2.8	3.1

Table A.1 (cont.)

V (cm) VERT	H (cm) HORZ	D (cm) DIST	F (per min)	ACTION LIMIT (AL)	DYNAM % CAP	ISOMETRIC % CAPABLE		BACK COMPRESS.		MET. RATE	
						LOWER	UPPER	LOWER	UPPER	LOWER	UPPER
75	15	25	<.2	40	---	48	54	306	404	1.8	1.8
			1	37	---	59	61	291	388	2.1	2.1
			10	7	---	--	--	151	240	2.4	2.5
75	15	75	<.2	32	---	76	77	268	363	1.8	1.8
			1	29	---	82	84	257	351	2.4	2.5
			10	5	---	--	--	145	234	3.2	3.3
75	45	25	<.2	13	---	86	97	289	364	1.8	1.8
			1	12	86	89	97	280	355	1.9	1.9
			10	2	99	--	--	167	245	2.1	2.2
75	45	75	<.2	11	---	94	99	258	347	1.8	1.8
			1	10	97	95	99	252	342	2.0	2.1
			10	2	99	--	--	162	240	2.5	2.6
75	75	25	<.2	8	---	77	80	353	389	1.8	1.8
			1	7	---	82	83	339	373	1.9	1.9
			10	1	---	--	--	250	272	2.1	2.2
75	75	75	<.2	6	---	86	86	325	357	1.8	1.8
			1	6	---	88	89	319	349	2.0	2.0
			10	1	---	--	--	244	265	2.4	2.5
125	15	25	<.2	32	---	--	97	245	---	1.5	1.5
			1	30	---	--	97	233	---	1.8	1.8
			10	11	---	--	--	105	---	2.5	2.5
125	15	75	<.2	26	---	--	99	204	---	1.5	1.5
			1	24	---	--	99	195	---	2.1	2.1
			10	9	---	--	--	92	---	3.7	3.7
125	45	25	<.2	11	---	--	94	182	---	1.5	1.5
			1	10	90	--	94	177	---	1.6	1.6
			10	4	99	--	--	100	---	2.0	2.0
125	45	75	<.2	9	---	--	96	160	---	1.5	1.5
			1	8	98	--	97	155	---	1.7	1.7
			10	3	99	--	--	89	---	2.5	2.5
125	75	25	<.2	6	---	--	91	326	---	1.5	1.5
			1	6	---	--	93	318	---	1.6	1.6
			10	2	---	--	--	257	---	1.9	1.9
125	75	75	<.2	5	---	--	95	303	---	1.5	1.5
			1	5	---	--	95	303	---	1.7	1.7
			10	2	---	--	--	249	---	2.3	2.3

Table A.1 (cont.)

V (cm) VERT	H (cm) HORZ	D (cm) DIST	F (per min)	ACTION LIMIT (AL)	DYNAM % CAP	ISOMETRIC % CAPABLE		BACK COMPRESS.		MET. RATE	
						LOWER	UPPER	LOWER	UPPER	LOWER	UPPER
150	15	25	<.2	28	---	--	73	230	---	1.5	1.5
			1	26	---	--	80	215	---	1.8	1.8
			10	9	---	--	--	109	---	2.5	2.5
150	15	50	<.2	24	---	--	85	200	---	1.5	1.5
			1	22	---	--	89	191	---	1.9	1.9
			10	8	---	--	--	96	---	3.0	3.0
150	45	25	<.2	9	---	--	95	247	---	1.5	1.5
			1	9	97	--	97	236	---	1.6	1.6
			10	3	99	--	--	174	---	2.1	2.1
150	45	50	<.2	8	---	--	98	225	---	1.5	1.5
			1	7	99	--	99	220	---	1.7	1.7
			10	3	99	--	--	168	---	2.3	2.3
150	75	25	<.2	6	---	--	P	P*	---	1.5	1.5
			1	5	---	--	P	P	---	1.6	1.6
			10	2	---	--	--	P	---	2.0	2.0
150	75	50	<.2	5	---	--	P	P	--	1.5	1.5
			1	4	---	--	P	P	---	1.6	1.6
			10	2	---	--	--	P	---	2.1	2.1
175	15	25	<.2	24	---	--	97	196	---	1.5	1.5
			1	22	---	--	98	184	---	1.7	1.7
			10	8	---	--	--	95	---	2.5	2.5
175	45	25	<.2	8	---	--	P	P		1.5	1.5
			1	7	99	--	P	P		1.6	1.6
			10	3	99	--		P		2.1	2.1

*The currently available models suggest that reach posture (P) rather than strength is most limiting in these cases.

Table A.2: Maximum Permissible Limit Sensitivity Analysis

V (cm) VERT	H (cm) HORZ	D (cm) DIST	F (per min)	MAX PERMIS (MPL)	DYNAM % CA	ISOMETRIC % CAPABLE		BACK COMPRESS.		MET. RATE	
						LOWER	UPPER	LOWER	UPPER	LOWER	UPPER
15	15	25	<.2	91	---	53	64	255	786	2.2	2.2
			1	84	---	67	76	244	730	2.8	3.0
			10	15	---	--	--	140	256	4.6	5.8
15	15	75	<.2	73	---	82	85	227	654	2.2	2.2
			1	67	---	86	88	218	612	3.5	3.8
			10	12	---	--	--	136	237	5.8	7.3
15	45	25	<.2	30	---	69	80	456	583	2.2	2.2
			1	28	32	75	84	435	547	2.5	2.6
			10	5	97	--	--	245	267	4.1	5.1
15	45	75	<.2	24	---	81	89	406	505	2.2	2.2
			1	22	59	86	91	384	475	2.7	2.9
			10	4	98	--	--	233	258	4.6	5.6
15	75	25	<.2	18	---	36	48	501	660	2.2	2.2
			1	17	---	41	52	482	635	2.4	2.6
			10	3	---	--	--	295	390	4.0	5.0
15	75	75	<.2	15	---	61	73	451	594	2.2	2.2
			1	13	---	66	77	432	573	2.6	2.7
			10	2	---	--	--	283	375	4.2	5.3
50	15	25	<.2	108	---	40	73	809	911	2.2	2.2
			1	99	---	52	79	764	848	2.8	3.0
			10	18	---	--	--	284	360	3.9	4.7
50	15	75	<.2	86	---	71	85	700	758	2.2	2.2
			1	79	---	80	89	664	706	3.6	3.8
			10	14	---	--	--	259	342	5.6	6.3
50	45	25	<.2	36	---	60	75	621	710	2.2	2.2
			1	33	13	66	79	595	680	2.4	2.5
			10	6	95	--	--	262	361	3.3	3.8
50	45	75	<.2	29	---	76	90	551	629	2.2	2.2
			1	26	39	80	92	528	601	2.7	2.8
			10	5	97	--	--	250	351	3.9	4.5
50	75	25	<.2	22	---	49	64	634	706	2.2	2.2
			1	20	---	55	75	609	673	2.4	2.5
			10	4	---	--	--	364	375	3.2	3.7
50	75	75	<.2	17	---	64	86	567	623	2.2	2.2
			1	16	---	69	88	544	598	2.6	2.6
			10	3	---	--	--	350	358	3.6	4.1

Table A.2 (cont.)

V (cm) VERT	H (cm) HORZ	D (cm) DIST	F (per min)	MAX PERMIS (MPL)	DYNAM % CAP	ISOMETRIC % CAPABLE		BACK COMPRESS.		MET. RATE	
						LOWER	UPPER	LOWER	UPPER	LOWER	UPPER
75	15	25	<.2	120	---	11	17	725	878	2.2	2.2
			1	110	---	20	26	677	827	2.8	2.9
			10	20	---	--	--	256	372	3.6	3.7
75	15	75	<.2	96	---	37	44	611	755	2.2	2.2
			1	88	---	48	55	574	7	3.8	3.8
			10	16	---	--	--	237	351	5.4	5.5
75	45	25	<.2	40	---	55	68	626	757	2.2	2.2
			1	37	5	62	75	592	722	2.4	2.4
			10	7	94	--	--	260	360	2.8	2.9
75	45	75	<.2	32	---	73	85	538	668	2.2	2.2
			1	29	25	78	90	513	643	2.7	2.8
			10	5	96	--	--	245	345	3.5	3.7
75	75	25	<.2	24	---	47	56	674	726	2.2	2.2
			1	22	---	54	64	641	688	2.3	2.4
			10	4	---	--	--	366	389	2.6	2.8
75	75	75	<.2	19	---	64	74	599	642	2.2	2.2
			1	18	---	69	79	579	619	2.5	2.6
			10	3	---	--	--	352	374	3.2	3.3
125	15	25	<.2	96	---	--	14	689	---	1.9	1.9
			1	90	---	--	20	646	---	2.4	2.4
			10	32	---	--	--	260	---	4.0	4.0
125	15	75	<.2	77	---	--	38	560	---	1.9	1.9
			1	72	---	--	47	527	---	3.2	3.2
			10	26	---	--	--	218	---	6.8	6.8
125	45	25	<.2	32	---	--	74	483	---	1.9	1.9
			1	30	8	--	78	460	---	2.1	2.1
			10	11	79	--	--	208	--	2.7	2.7
125	45	72	<.2	26	---	-	85	401	---	1.9	1.9
			1	24	22	--	88	384	---	2.3	2.3
			10	9	89	-	--	185	---	3.8	3.8
125	75	25	<.2	19	---	--	71	620	---	1.9	1.9
			1	18	---	--	75	600	---	2.0	2.0
			10	6	---	--	---	398	---	2.5	2.5
125	75	75	<.2	15	---	--	81	560	---	1.9	1.9
			1	14	---	--	84	544	---	2.2	2.2
			10	5	---	-	--	375	---	3.2	3.2

Table A.2 (cont.)

V (cm) VERT	H (cm) HORZ	D (cm) DIST	F (per min)	MAX PERMIS (MPL)	DYNAM % CAP	ISOMETRIC % CAPABLE		BACK COMPRESS.		MET. RATE	
						LOWER	UPPER	LOWER	UPPER	LOWER	UPPER
150	15	25	<.2	84	---	--	42	623	--	1.9	1.9
			1	78	---	--	54	584	--	2.4	2.4
			10	28	---	--	--	249	--	3.9	3.9
150	15	50	<.2	71	---	--	68	539	--	1.9	1.9
			1	67	---	--	77	508	--	2.7	2.7
			10	24	---	--	--	218	--	5.1	5.1
150	45	25	<.2	28	---	--	79	437	--	1.9	1.9
			1	26	---	--	84	198	--	2.0	2.0
			10	9	88	--	--	198	--	2.8	2.8
150	45	50	<.2	24	---	--	87	378	--	1.9	1.9
			1	22	34	--	89	361	--	2.2	2.2
			10	8	95	--	--	175	--	3.2	3.2
150	75	25	<.2	17	---	--	81	567	-	1.9	1.9
			1	16	---	--	86	543	--	2.0	2.0
			10	6	---	--	--	365	--	2.6	2.6
150	75	50	<.2	14	---	--	89	519	--	1.9	1.9
			1	13	---	--	91	503	--	2.1	2.1
			10	5	---	--	--	350	--	2.9	2.9
175	15	25	<.2	72	---	--	13	544	--	1.9	1.9
			1	67	---	--	22	513	--	2.3	2.3
			10	24	---	--	--	223	--	3.7	3.7
175	45	25	<.2	24	---	--	95	487	--	1.9	1.9
			1	22	33	--	97	464	--	2.0	2.0
			10	8	---	--	--	286	--	2.8	2.8

☆ U.S. GOVERNMENT PRINTING OFFICE: 1981—757-074/1080