MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

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SECTION 8

HUMAN FACTORS, ERGONOMICS, AND HUMAN RELATIONS

CHAPTER 1
MANUFACTURING ERGONOMICS

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The engineering of world class manufacturing facilities requires an unprecedented level of attention to the human factor. As product differentiation becomes more difficult to achieve solely on technological grounds, facility and process design must now be fused into the product development cycle. This is known as building quality into the process. The common denominator in this equation is the ubiquitous customer, with the concept of customer extending from the purchaser of the product to the individuals building the products. This sensitive, pragmatic, and somewhat egalitarian view toward the utilization of labor has developed into a survival tactic for sophisticated manufacturing organizations. Successfully addressing the human-equipment interface requires a broad and strong ergonomics knowledge base.

Ergonomics is a young science which grew out of the need to better accommodate military personnel during World War II. It is ironic that what was developed as a tool to make fighting more efficient is now the preferred technique for preventing musculoskeletal injuries in the workplace. As an interdisciplinary science, ergonomics draws its knowledge from several main tributaries (Fig. 1.1).

The practice of ergonomics began with the collection and use of anthropometric data. These data combined with observations were used to estimate the "goodness-of-fit" between equipment and personnel. Early ergonomists were concerned with accommodating variously sized individuals. As performance requirements became more critical, size considerations were expanded to encompass strength, reach, vision, cardiovascular capabilities, cognition, mission survivability, and most recently cumulative musculoskeletal injury. The last of these concerns addresses the question "Why ergonomics?" In traditional manufacturing environments, safety and health concerns are separated from manufacturing and design concerns, with one group being in personnel and the other in production or

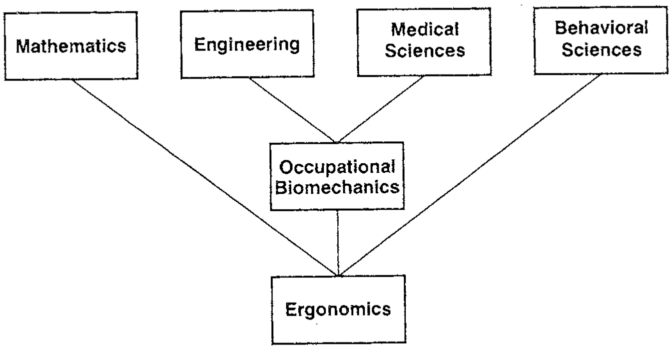

FIGURE 1.1 The science of ergonomics. (*Imai, 1986.*)

research and development. This suggests a fundamental problem indigenous to interdisciplinary sciences: addressing heretofore separate problems in a parallel manner. In a sense, biomechanically based ergonomics has taught us of the connectivity between product manufacturing and health management. Bridging the personnel gap between pure safety concerns and pure engineering concerns remains a major challenge in the practice of manufacturing ergonomics. The solution is to learn more. Both safety experts and industrial engineers need to become familiar with occupational biomechanics, the discipline which allows us to quantify forces on and within the human body at work. It is this measurement-based science which is largely responsible for the advances made in musculoskeletal injury prevention during the last decade. More to the point, biomechanics is a major tool for optimizing manufacturing facilities, addressing both economic and safety concerns.

Using biomechanics, it is possible to measure low-level, cumulative force exposures to the body. Using these measurement tools combined with necessary exposure limits it is possible to prevent musculoskeletal injuries from occurring. This measurement base also provides the quantitative basis for better utilization of human capabilities, or improved "fit."

The large current focus on quality improvement as a competitive advantage is a logical position once it's realized that well-distributed technology and capital require a new front on which to wage and acquire a strategic advantage. Though simplistic, process-driven advantages have been the mainstay of successful corporations in the 1980s. In the 1990s and beyond, process improvements will dominate competitive agendas. Ergonomics is a process for refining manufacturing systems and products through the study of how they interact with their users. Biomechanics is the decision tool. As such, ergonomics is a high-technology improvement process. These are the two basic differences between ergonomics and other process improvement strategies, that is, quality circles, Kaizen,* and the like.

As programs for continuous improvement (Kaizen in Japanese) have demonstrated both quality and cost advantages in the manufacturing and design process, they deserve careful study. The focus on the person-process, rather than the results is the main point of Kaizen. Kaizen is an extension of the Taoist philosophy applied to pragmatic business improvement. The results have been nothing short of astonishing.

According to Imai (1986), there are two main approaches to industrial progress, the relentless gradual effort and the great leap forward. As manufacturing becomes more sophisticated, differences in approach as contrasted with differences in technology may translate into significant differences in market penetration, quality, and customer satisfaction. In a sense the antonym for Kaizen is innovation. In the eastern countries (that is, Japan) the philosophy drives the process, whereas in the west the results feature the philosophy. Herein lies the difference: Kaizen, although originally an American idea (Deming et al.,

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*Kaizen is a trademark of the Kaizen Institute, Ltd.

TABLE 1.1 Kaizen versus Innovation

	KAIZEN	INNOVATION
Effect	Long-term and long lasting but undramatic	Short-term but dramatic
Pace	Small steps	Big steps
Timeframe	Continuous and incremental	Intermittent and non-incremental
Change	Gradual and constant	Abrupt and volitile
Involvement	Everybody	Select few champions
Approach	Collectivism, group efforts, systems approach	Rugged individualism in ideas & efforts
Mode	Maintenance and improvement	Scrap and rebuild
Spark	Conventional know-how and state-of-the-art	Technological breakthroughs, new theories
Practical requirements	Requires little investment but great effort to maintain it	Requires large investment, but little effort to maintain it
Effort orientation	People	Technology
Evaluation criteria	Process and efforts for better results	Results for profit
Advantage	Works well in slow growth economy	Better suited to fast growth economy

Source: Imai, 1986.

1950s), is culturally better suited to an eastern approach to manufacturing as compared with innovation-driven industry. Imai's list comparing Kaizen qualities with those of innovation clarifies the distinction (Table 1.1).

From a competitive, industrial engineering perspective, how is the manufacturing advantage to be realized? The concept is to use ergonomics as a high-technology, Kaizen tool. Ergonomics is a process tool which naturally incorporates innovation. Rather than being individual-oriented continuous improvement (Kaizen), ergonomics is interface-oriented continuous improvement. The technology is a necessary component to this approach, as interface assessments require primarily quantitative rather than intuitive tools because of their complexity. Biomechanics is the tool.

In our experience, this approach to continuous improvement provides greater power and agility in the addressing of protean manufacturing problems when compared with Kaizen. Of course, ergonomics may be considered a Kaizen "type" tool. A systematic approach to bringing ergonomics into the manufacturing process is now termed total ergonomic quality (TEQ). This is a complete corporatewide program for ensuring ergonomic quality throughout design, production, and marketing (Fig. 1.2).

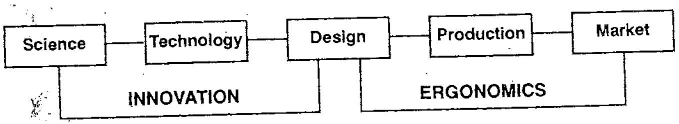

FIGURE 1.2 Innovation versus ergonomics. (*Imai, 1986.*)

TEQ starts with the training of management, engineers, and line employees in ergonomic techniques and responsibilities. TEQ ends with training and sharing the results of implementing ergonomics with the same individuals. Between these ends are process improvements utilizing ergonomic-engineering techniques. These techniques utilize biomechanics and statistical analysis tools (Table 1.2).

TABLE 1.2 Basic Statistical Analysis and Biomechanical Tools Utilized within a Manufacturing Ergonomics Program

STATISTICAL TOOLS	BIOMECHANCIAL TOOLS
Pareto diagrams	Dynamic Biomechanical Models
Cause-effect diagrams	Quantitative Muscle Measurement (EMG)
Histograms	Flexible Force Measurement Systems (FFM)
Control charts	Human Computer Aided Design
Scatter diagrams	Ergonomic Data Bases
Check Sheets	Cardiovascular measurements of fatigue
Relations diagram	Human motion tracking (video, sonar, infrared)
Affinity diagram	Musculoskeletal questionniares
Tree diagram	
Matrix diagram	
Matrix data-analysis diagram	
Process decision program chart	
Arrow diagram	

"What is ergonomics?" and "How is it used?" are the first topics this chapter addresses.

ERGONOMICS FOR PREVENTING WORKPLACE INJURIES

Back Injuries. Apart from headaches, low back pain is the largest cause of pain in the United States (Khalil, 1984) and the major reason for physician contact (Mandell et al., 1989). Despite improved medical care, automation, and preemployment examinations, there has been little decline in back injuries (Ayoub and Mital, 1989).

There is little doubt that back injury is mainly caused by the nature of the individuals' work. Snook (1978) showed a high correlation between the specific act at work and the compensable back injury. Svensson and Anderson (1983) found heavy work to be strongly correlated to low pack pain. In this study, the heaviest tasks had the highest incidence of pain.

Back pain follows a highly remissive and recurring pattern. Attacks of back pain are self-limiting; regardless of the treatment used, most people feel better in 4 weeks and 90 percent spontaneously heal in 3 months. About 70 to 80 percent of low back pain attacks recur.

Nurses have among the highest incidence of occupational back injury (Jensen, 1985, 1986; Klein, 1984; Harber et al., 1985). The repeated lifting and moving of patients is suggested as the cause. A review of back injuries in 26 states (U.S. Department of Labor, 1982) showed that they occurred under the following conditions:

- The majority of movements at the time of injury were bending and twisting.
- The average duration an object was held at the time of injury was less than 1 minute.
- Of those who report a back injury, 30 percent lift over 100 times a day.
- The average weight of the object lifted at the time of injury was 40 to 100 lb (18.1 to 45.3 kg) in 70 percent of the cases and over 100 lb (45.3 kg) in 30 percent.
- The distance the load was carried in 80 percent of the back injury cases was less than 5 ft (1.52 m).
- The position of the load at the time of injury was on the floor in 50 percent of the cases.
- 35 percent of the workers felt that the loads they lifted were too heavy.
- About 50 percent of the workers who reported injuries had prior back injury.
- The position of the back at the time of the injury was fully or partially flexed in 83 percent of the injuries.

TABLE 1.3 Medical, Social, Psychological, and Other Risk Factors for Low Back Pain

Constitutional:	Age, weight, height, back muscle strength, fitness, back mobility, genetic factors.
Medical:	Severe scoliosis, difference in length of legs, multi-level degeneration, disc resorption, disc herniation, severe arthrosis facets, spondylarthropathies, spondylolysis, spondylolisthesis, sacralisation/transitional vertebra, skeletal defects, fractures, neoplasmata, severe kyphosis, lumbar kyphosis, gravities.
Psychosocial:	Depression, anxiety, family problems, hypochondriasis, somatization, dissatisfaction with work and a high degree of responsibility.
Demographic:	Socio-economic and educational level, location of home.
Other:	Sports and level of activity, gardening, smoking, alcohol consumption, coughing.

Source: Hildebrandt, 1987.

Other risk factors include body constitution, postural problems, skeletal and medical problems, and psychosocial and demographic factors as shown in Table 1.3.

Hand, Arm, and Wrist Injury. Injuries in the region between the hand and shoulder often belong to the category known as repetitive strain injuries (RSI). They are also referred to as cumulative trauma disorders or repetition injuries (Fraser, 1989; Sheng and Gross, 1988). RSIs are due to inflammation, pain, swelling or tenderness in tendons, nerves, synovial sheaths, synovial membranes, the lateral and medical epicondyles, and bursae. The most common RSIs are tendonitis, synovitis, tenosynovitis, epicondilytis, bursitis, and carpal tunnel syndrome.

Tenosynovitis affects the tendons and sheaths at the wrist; epicondilytis affects the muscles that originate at the epicondyles of the elbow; and carpal tunnel syndrome afflicts the median nerve as it passes through the carpal tunnel. It has been recognized that repetitiveness alone is not a good characterization of the condition; in many cases it may be caused by static forces. Though we use the term repetitive strain injury because of its familiarity, occupational overuse injury better explains the condition without necessarily linking it to repetitiveness.

More than one repetitive strain injury may occur simultaneously. The pattern of occurrence noted among a sample of women (Brown and Dwyer, 1984) is a useful pointer for the need for early intervention when symptoms first appear. Women with one RSI condition continued working and developed other conditions; the presence of one condition in a limb led to others in the same limb; resting one arm led to the appearance of problems in the other arm; inadequate rest following trauma or surgery led to the development of a new injury.

High-incidence patterns of RSI have been reported among certain types of work. A sample of these is shown in Table 1.4. Recently in the United States, the meat-packing industry has been focused on by the Occupational Safety and Health Administration (OSHA) for a "national special emphasis program" because of the high incidence of repetitive stress injuries (Bureau of National Affairs, 1990).

The risk factors for repetitive stress injuries have not been conclusively established, particularly because RSIs cover a wide range of symptoms. Some high-risk situations that have been suggested include tools and workplace equipment that cause extreme deviation of the hand and wrist, work surfaces that are too high or too low, tools or processes which require high hand forces, and the use of vibrating tools. Further, leisure activities which

TABLE 1.4 Work Types with High Incidences of RSI

Work Type	Specifics	Reference
Electrical and electronic	Winding wires and using small hand tools	Fraser, 1989
Poultry and meat fleshing boning and packaging	Use of knives and small tools and the lifting of carcasses.	Armstrong, 1982; Kivi, 1984
Manual sewing	Especially leather, canvas and heavy material.	Fraser, 1989
Word and data processing		Pinkham, 1988

require actions similar to those that caused the problem at work may contribute to the development of RSI in nonwork environments.

The Importance of Matching Workplaces to Human Capabilities. If stressors in the workplace are reduced and operator comfort enhanced, then it is very likely that workplace injuries will be reduced. Physical and cognitive work involves the interaction between humans and machines. The elements of a human-machine system are:

1. Human
2. Interface
3. Machine
4. Environment

Whenever these four elements are in harmony, the injury potential is minimized, if not eliminated. In a more explicit sense and in a manufacturing context this implies that the human capabilities should match the task at hand. Any mismatches or poor fits are potential contributors to error and injury.

The Role of Ergonomics in Workstation Layout and Injury Prevention. As defined before, ergonomics is the science dealing with work laws for humans. The key principles underlying this study encompass the man-machine system such that the human capabilities match the requirements of the job components, interface-machine-environment.

In the area of manufacturing, an inappropriate workstation layout may lead to a job stressor when its use exceeds the capabilities of the human operator. For example, when the reach and bending requirements or the frequency of each component task increases, back and hand injuries potential increases. The extent of the mismatch is best evaluated through a task analysis, which will be discussed later in this chapter. The accommodation of all individuals is achieved through adjustability. Ergonomics, when applied to layout and design, will help prevent injuries, improve performance, and improve operator well-being.

Workplace and Tool Considerations for Minimizing Wrist Injuries. The reduction of stress to the wrist may be achieved by making sure that the following principles are adhered to:

Keep the Wrist Straight. By maintaining a neutral wrist position during repetitive workplace activities, the amount of flexion, extension, and ulnar and radial deviation of the wrist is, by definition, minimized. As repetitive and forceful flexion or extension movements of the wrist are thought to gradually damage the median nerve, a wrist maintained in a nearly straight or neutral position will be less likely to sustain injury during repetitive motion activities.

Methods for ensuring that the wrist is maintained in as neutral a position as possible for a specific workplace activity include:

1. Biofeedback training
2. Task-specific tool selection
3. Task-specific workstation layout

Reduce the Transmission of Vibration to the Hand. Low-frequency vibration (10 to 60 Hz) has been found to contribute to cumulative trauma disorders such as Raynaud's disease and vibration white finger. Thus, by reducing the transmission of vibration to the hand during the use of vibratory hand tools, it may be possible to reduce these vibration-related disorders. Methods for reducing vibration transmission include:

1. Vibration damping of the tool or workstation
2. Personal protective equipment use (warm, dry gloves with or without viscoelastic inserts)
3. Limiting daily exposure time

Keep Forward Reaches Short. Acceptable limits of reaching should consider the reach frequency, body size of the worker population, and the distance and force required during each reach. Workstations and work methods should be designed so that workers are not required to perform extensive reaches on a repetitive basis.

Select Appropriate Hand Tools. Ensure that the fit between the user and the tool is good and that the tool characteristics fit the required use. Factors which should be considered in handtool selection include weight, size, shape, ease of control, and surface texture. Tool characteristics should match the task requirements; for example, discrimination should be made between power and precision operations.

Evaluate the Mechanical Advantage of Tools. Whenever possible, let the tool do the work instead of the user. This can be accomplished through semiautomation or by choosing a tool which provides adequate leverage to minimize force required during task performance.

Evaluate the Gripping Surfaces to Ensure High Coefficients of Friction and Smooth Edges. The potential for tool slippage may be minimized by selecting a tool which provides a gripping surface and shape which matches the geometry of the hand posture required. Slip-resistant surfaces can be provided through granulated surfaces, rubber coatings, and rounded serrations.

Bend the Tool, Not the Wrist. Tasks which require *frequent and similar* wrist deviations are best accommodated with tools bent in the direction of hand or wrist deviations. Modified hand tools are highly task-specific. A tool alone cannot be ergonomic. To have an ergonomic situation, you must carefully define the circumstance of use and the working population. The label "ergonomic" describes the interaction between the tool, the user, and the work process. The amount of bend in a handle is highly task-specific. As an example, a recent study by Konz (1986) indicates that for simple nail driving, hammers with a 10° bend are preferred over straight and highly bent models.

Stay Close to the Body's Center of Mass. A well-designed hand tool should be usable as close to the center of mass as possible. This reduces bending and twisting movements as well as the magnitude of static muscle contractions (Fig. 1.3). Thus holding tools closer to the body improves control, comfort, and endurance. For many tools, shorter reaches also increase the amount of torque that can be applied.

Avoid Stress Concentrations. The holding surface of the tool should be large enough and contoured in such a manner that it will distribute contact forces over the largest practical area of the hand (Fig. 1.4).

Maintain Sharpness of Cutting Tools at All Times. Inadequately sharpened blades may significantly increase the amount of wrist force necessary to perform cutting operations. Blades which are easily changed or sharpened at the workstation should be utilized for repetitive cutting operations.

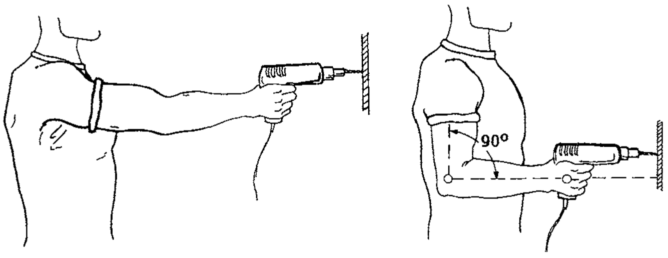

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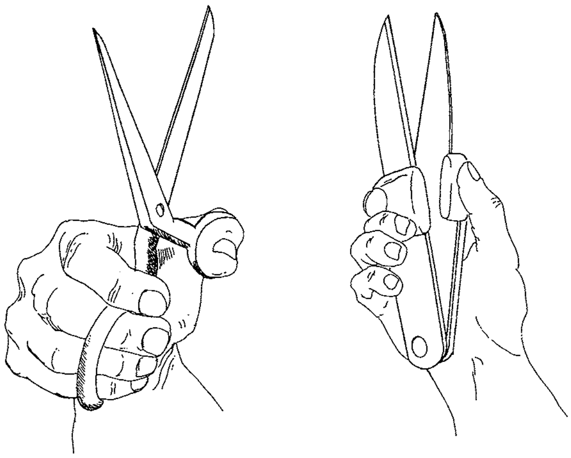
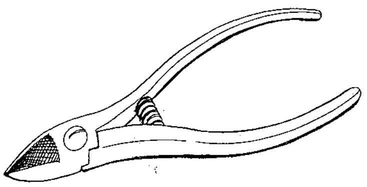
FIGURE 1.3 Illustration of tool held at center of mass.



Traditional Scissors

Modified Scissors with Spring Loaded Mechanism

FIGURE 1.4 Distribution of contact forces through tool design.



Traditional Wire Cutters with Spring

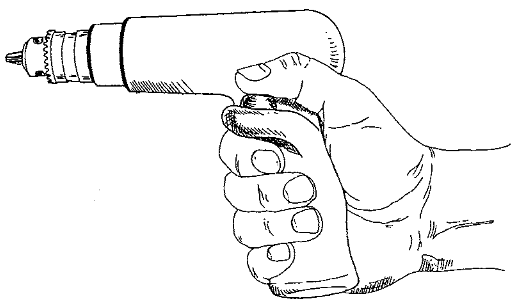
FIGURE 1.5 Spring-loaded mechanism in tool design.

Closing Tools Should Have Spring-Loaded Mechanisms. This provides better tool control and requires less muscle force to operate (Fig. 1.5).

Tool Sizing. To minimize flexor muscle activity and wrist force, a hand tool should fit the hand of the user (Fig. 1.6). The ability to grip a tool depends on hand size, surface contour, surface material, and handle width (separation).

Hand Tool Design. Hand tools extend capability of the hand. The following principles will assist you in the selection of tools.

Design Tools to Be Used by Either Hand. Without tools, the preferred hand is 5 to 15 percent faster and stronger than the nonpreferred hand. With tools, the advantage in performance of the preferred hand depends on the type of tool. With simple tools, such as an electric drill, the speed advantage is about 10 percent. The speed advantage for tools requiring some movement (hand saws, hammers) is 40 percent; for those requiring manipulation (scissors) it is 50 percent.



Power drill with grip handle that fits the shape of the hand

FIGURE 1.6 Proper handtool sizing.

There are two main reasons why tools should be designed to be used by either hand. First, the preferred hand is not always the right hand. For about 10 percent of the population it is the left hand. Second, if a tool can be used by either hand it can be used alternatively—first with the preferred hand and then with the nonpreferred hand. This not only improves productivity since the hand can rest while the person continues working but also reduces repetitions on each wrist—very important for preventing carpal tunnel and tenosynovitis problems.

Power with Motors More than Muscles. As pointed out above, electrical or compressed air power is inexpensive. Power tools permit speeds, forces, and capabilities far in excess of that furnished by human muscles. Battery-operated power tools permit more safety (no danger from electrical shorts) as well as improved convenience.

Use a Power Grip for Power; Use a Precision Grip for Precision. Although there are a number of grips, the most important are the power grip and the precision grip. Force can be (1) parallel to the forearm (suitcase handle, electrical drill, pistol), (2) at an angle (hammer, pizza cutter, reverse-grip pliers), or (3) torque about the forearm (corkscrew with a T handle).

Precision grips have a pinch grip by the thumb versus the first finger (or first and second finger). Precise control is needed for the tool shaft. When the tool shaft is under the thumb, the grip is called internal. When the tool shaft is above the thumb, the grip is called external.

Make the Grip the Proper Thickness, Shape, and Length. Every tool has two ends—one working on the material, the other on the hand. Female hands tend to be smaller than male hands; thus hand tools designed for men tend to be too large for women.

For a power grip, the best diameter is 1 to 2 inches; the most common mistake is a too small diameter (say 0.5 inch) handle which cuts into the hand. To prevent rotation of the tool in the hand, a bearing surface helps. A spherical handle is another alternative; although there are no bearing surfaces, the large contact area permits lower pressure. If the tool is to rotate in the hand, the area within the pinch grip should be circular to permit simple finger movements. A change in the cross section along the tool grip axis (1) reduces movement of the tool in the hand, (2) permits more force to be exerted, and (3) may act as a shield. A pommel (a shield at the rear of the handle) permits greater force when the tool is pulled toward the body. Finger grooves are not recommended since they do not fit all size hands. A wedge shape (gradual change in diameter) is better. The length for a power grip should be at least 4 inches (5 may be better) so all four fingers can grip.

For an external precision grip, the length should be at least 4 inches so the tool can be supported by the base of the thumb and first finger. For an internal precision grip, a short shaft tends to dig into the palm, so the shaft should be long enough to extend beyond the palm.

Design the Grip Surface to Be Compressible, Nonconductive, and Smooth. A compressed grip is easier on the hand, giving a better coefficient of friction and reducing vibration. Use rubber or wood and avoid hard plastic and metal. Grips should not conduct heat or electricity. Grips which are not conductive gain heat more slowly and as a result do not get as hot. The grip should release slowly to the hand so that the user can let go before being burned. A knife works by exerting a force over a very small area. Sharp edges on the tool handle act as knives to the hand. Grind away sharp edges, cover them with tape, or dip the handle into plastic. A sign of a poor grip is a mark left on the hand.

Consider the Angles of the Forearm, Grip, and Tool. The best position for the wrist is the "handshake" position. A contorted wrist leads to problems. Following the ergonomic philosophy that equipment should adjust to people rather than people adjusting to equipment: If a bend is needed, it should be in the tool, not the wrist.

Sufficient clearance also is needed to prevent burns and pinch points. It is desirable to have a spring keeping the tool normally open. Without the spring, there is the temptation to insert a finger between the handles to open them; the finger usually gets pinched. Tool handles, especially locking handles or toggle clamps, should have at least a 1-inch opening in their fully closed position.

Use the Appropriate Muscle Group. The fingers should be used for manipulative work; let the strong muscles of the forearm do the power work. The force of the tool is furnished by the forearm muscles rather than finger muscles. Another common problem is "trigger finger," due to repetitive use of the first finger or thumb. A trigger strip actuated by two to four fingers is the preferred alternative.

Workstation Adjustment Checklist

In addition to tool considerations, the workstation must be evaluated. For seated work, review the workstation checklist in Table 1.5. The key principle is adjustability. Operators must be familiar with all adjustment features and principles of proper workstation and work method fit. Adequate adjustable support for the back, arms, and legs is necessary to reduce cumulative static muscle forces.

Table 1.6 presents an overview of ergonomic intervention strategies for managing cumulative trauma disorders.

HUMAN ANTHROPOMETRY

Overview

Anthropometry is a principal branch of anthropology which deals with the measurement of the human body. Anthropometric variables refer to the characteristics of the body that can be standardized. The science of human measurement drew increased interest with the development of ergonomics, primarily when designing jobs and machines to "fit" the human. The goal of ergonomics is to make workplaces, equipment, and products fit the potential human users' capacities for reach, grasp, and clearance.

A feeling of "ownership" is present whenever a good or product fits a person. In a man-machine environment, such ownership can be brought about by designing machines and equipment to accommodate the body measurements and capabilities of the potential user population. Within reasonably homogeneous populations, it is empirically true that anthropometric measures conform to a bell-shaped curve or a gaussian distribution (Fig. 1.7).

A common concept in the area of anthropometry is *percentile*. The xth percentile is defined as the point where x percent of the population has the same value or less than that value for a given measurement. For example, if stature is the variable of interest, a human with a 95th percentile height would be taller than 95 percent of a given population. Alter-

TABLE 1.5 Workstation Checklist

	YES	NO	N/A
1. Is the height of the worksurface adjustable to accommodate different operators?			
2. Is there sufficient space for temporary storage at the workplace?			
3. Are there inefficient work motions because of workspace layout?			
4. Is there sufficient clearance for handling or maintenance tasks?			
5. Is the worktable adequate for the smallest and largest worker for reach and clearance?			
6. Is there sufficient lighting at the workplace?			
7. Is there too much glare at the workplace?			
8. Is there too much noise at the workplace?			
9. Are there gaseous fumes in the area?			
10. Is the workplace temperature between 68° and 78°F.			
11. Is the air circulation good?			
12. Is the seat used suitable for the task?			
13. Is the chair height adjustable and easy to adjust?			
14. Is the chair backrest easily adjustable?			
15. Is a footrest provided?			
16. Is the footrest large enough to support both feet and allow a change of position?			

natively, one may say that only 5 percent of the people are taller than the 95th percentile individual.

The two parameters that describe the gaussian distribution are the mean (m) and the standard deviation (s). The pth percentile (Table 1.7) of a gaussian variable (X_p) can then be found by using $X_p = m + sz$, where z is the standardized normal deviation found in any statistics text. A few commonly used values in the design of man-machine systems are shown in Table 1.7.

Measurement Instrumentation. The standard anthropometric measurement instrument is the anthropometer. This is a rigid rod 2 m long, with two counterreading scales. Commonly, the rod is split into three or four sections which fit into one another. Elaborate anthropometers are fitted with mechanical or electronic reading devices. A stadiometer is a fixed anthropometer, primarily used for the measurements of stature. For transverse diameters, calipers may be used. A pelvimeter measures up to approximately 600 mm and the cephalometer up to approximately 300 mm. Skinfold thickness is measured with a constant-pressure skinfold caliper with a pressure of 10 g per mm^2. For arcs and girths, a flexible steel tape with a flat section may be used. It is undesirable to use self-straightening steel tapes. Goniometers are used to measure angles. Electrogoniometers (or elgon) are electrical potentiometers which can be calibrated to read angles. When a constant voltage is applied to the elgon, the resistance is a function of the angle.

TABLE 1.6 Ergonomic Intervention Strategies for Wrist Injury Prevention

PROBLEM:	POSSIBLE RECOMMENDATION:
1. REPETITIVENESS	1. Use mechanical aids
	2. Enlarge work content
	3. Rotate workers
	4. Spread work uniformly across workshift
	5. Automation
2. LARGE JOINT FORCES	1. Increase mechanical advantage of tools
	2. Decrease the weight of tools, containers and parts
	3. Increase the friction between handles and the hand
	4. Optimize size and shape of handles
	5. Select gloves to minimize effects on performance
	6. Balance hand-held tools and containers
	7. Use torque control devices
	8. Fine tune work/rest ratios
	9. Mechanical assists
	10. Automation
3. LARGE HAND/ARM CONTACT FORCES	1. Enlarge corners and edges
	2. Pads and cushions
	3. Tool size selection
4. POOR POSTURE	1. Locate work properly
	2. Orient work properly
	3. Select tool dewsign for workstation
	4. Change work method
	5. Postural biofeedback training
5. VIBRATION	1. Select tools with minimum vibration
	2. Select process to minimize surface and edge finishing
	3. Mechanical assists
	4. Use isolation for tools that operate above resonance point
	5. Provide damping for tools that operate at resonance point
	6. Vibration damping gloves
	7. Adjust tool speed to avoid resonance

Source: Armstrong, T. J., and Lifshitz, Y., 1987.

TABLE 1.7 Values of Standard Normal Deviates

Percentile	z
2.5th	-1.96
5th	-1.64
50th	0.00
95th	+1.64
97.5th	+1.96

Adjustments to Measurement. Most measurements reported are for humans who are minimally clothed. When these data are to be used for design purposes, such measurements should be adjusted to account for clothing and posture. Clothing adjustments as estimated by Eastman Kodak (1983) are as follows:

+ 2.5 cm for standing height
+ 0.5 cm for sitting heights
+ 0.8 cm for breadths
+ 3.0 cm for foot length

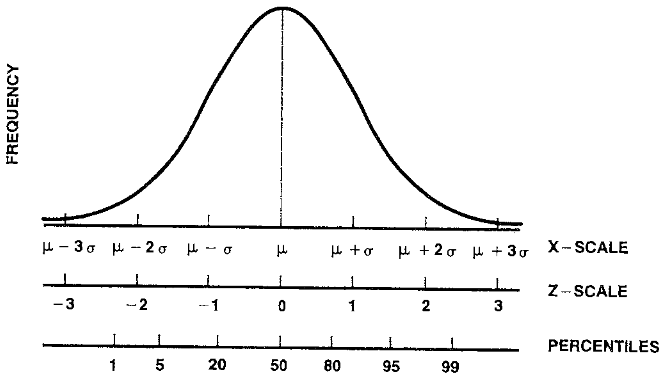


FIGURE 1.7 Percentiles and the z-statistic in a gaussian distribution.

Since measurements are made with the subject in an erect position, adjustments ought to be made also for postural slump. Estimated adjustments (Eastman Kodak, 1983) are

− 2.0 cm for standing height
− 4.5 cm for sitting height

Estimation. The designer is frequently required to estimate the distribution of some measures which may not be reported directly for a particular population. Under such circumstances they need to be estimated. A few useful techniques are:

Correlation and Regression. In the correlation and regression method, the assumption is that the correlation between two variables is the same for two populations (population 1 and population 2). The regression equation for population 1 is then used to estimate the unknown variables in population 2.

Sum and Difference Dimensions. In the sum and difference method specialized equations are used. When an unknown dimension is equivalent to the sum of two known dimensions a and b, the

$$m_{(a+b)} = m_a + m_b$$

$$s^2_{(a+b)} = s^2_a + s^2_b + 2rs_as_b$$

If the unknown dimension is the difference of two known dimensions, then

$$m_{(a+b)} = m_a - m_b$$

$$s^2_{(a-b)} = s^2_a + s^2_b - 2rs_as_b$$

where m_a and m_b = the two means of the known variables
a and b and s_a and s_b = the sample standard deviations of the same two variables
r = the sample correlation coefficient

Ratio scaling is commonly used (Barkla, 1961; Pheasant, 1986) for two populations (reference and target) similar in age, sex, and ethnicity. For two variables a and b

$$m_a/m_b \text{ (in population 1)} \sim m_a/m_b \text{ (in population 2)}$$

$$s_a/s_b \text{ (in population 1)} \sim s_a/s_b \text{ (in population 2)}$$

Anthropometric Data

Anthropometric data have been classified into two general classes: static and functional (dynamic) dimensions. Static data are obtained with the human in a standardized, static position, while functional (or dynamic) dimensions are obtained with the body being involved in some physical movement. Anthropometric literature of different countries has been published by many researchers. Two sources that list a few different countries are Garret (1971) and Pheasant (1986). A few others are presented in Table 1.8.

TABLE 1.8 Sources of Anthropometric Data

Population	Source
Egypt	Moustafa (1987)
Germany	Jurgens (1973), Kroemer (1964), Wagner (1988)
United Kingdom	Andrew and Manoy (1972), Davies et al. (1980), Haslegrave (1979, 1980, 1986), Montegriffo (1968), Murrell (1965), Pheasant (1982), Redgrove (1979)
France	Bouisset (1967), Bouisset and Monod (1961), Rebiffe et al. (1983), Wisner & Rebiffe (1963)
Hong Kong	Courtney (1984)
India	Eveleth & Tanner (1976), Goswami et al. (1987)
Japan	Yanagisawa (1974)
Korea	Fernandez (1989)
Netherlands	Molenbroek (1987)
Poland	Batogowska and Slowikowski (1974)
Sweden	Inglemark and Lewin (1968), Lewin (1969), Lindgren (1976), Thiberg (1965-1970)
Switzerland	Grandjean & Burandt (1962), Grandjean (1973)
United States	Armed Forces Personnel Clauser et al., (1972), Dempster (1955), Garret (1970, 1971), Hertzberg et al., (1954), Gordon et al (1989), NASA (1978), Van Cott and Kinkade (1972). Robinette and Fowler (1988) Civilian Personnel Diffrient et al. (1981), Kroemer et al., (1986), McFarland & Stoudt (1960), NASA (1978), Snyder et al. (1977), Van Cott and Kinkade (1972),
U. S. S. R.	Ermakova et al. (1985), U. S. Army Labcom (1986)

As may be evident, most of the data published are restricted to a few countries, making it very inconvenient for designers to quickly access information for global product design owing to the number of sources required. The anthropometric database ErgoBase™ (BCA, 1989) provides an alternative in the form of a computerized database compiling anthropometric data from many countries and special populations.

Uses of Anthropometric Data. The main purpose of measurement and estimation of anthropometric data is to design "machines" which enhance the fit with the intended users. By enhancing, it is meant that the design improves operator comfort and reduces the strain experienced by the body while working in the environment. People vary in size and strength. Hence no one design will be optimal for all users. In the application of anthropometric data to workplaces, products, and tools, the following methods may be employed.

Design for the Average. The design dimensions are based on the 50th percentile of the user population. Because of the variability, it is very desirable to design workplaces and equipment that are adjustable. Although adjustable features may be provided, they may not be utilized. Using the adjustability depends on the speed, training, and effort required and the degree of perceived benefit to the operator. The adjustments may not be required. However, the presence of adjustability will allow a larger population to work comfortably. The following two design methods are based on this concept.

Design for the Extreme Individual. The designs are based on the extreme size of an anthropometric variable(s) that the potential current user population possess. With a new design, this would indirectly translate to 100 percent of the population. In some cases, such a design would not be financially viable. For this reason, the general tendency is to design for a range of individuals.

Design for a Range. The range *normally* chosen in ergonomic practice is from the 5th percentile woman to the 95th percentile man. However, depending on the component or item being designed, the ergonomist may decide to use another suitable range. When designing for a range, the percentage of the population for which the item was designed is known as the *accommodated percentage* (McCormick and Sanders, 1982). Designing for a range is the most sensible approach for accommodating employees and customers.

Work Space. An element which goes hand in hand with anthropometry is work envelopes. The *functional arm reach envelope* is a work-space envelope in three-dimensional space that represents the limits of convenient arm reach. Such an envelope may be traced through the use of a reach anthropometer (Roth, Ayoub, and Halcomb, 1977). The reach areas for a seated 5th percentile female and the standing reach areas of one arm and both arms are shown in Figs. 1.8 and 1.9.

Computer-Aided Man-Machine System Design. Several computerized packages to evaluate human-machine fits have emerged over the past. The older models are BOEMAN (Ryan, 1971) and the crewstation geometry evaluator (CGE) (Katz, 1972). Both these models were not interactive and were batch-oriented, although the BOEMAN model did have the ability of producing a three-dimensional human on a screen.

A 2-D graphic aid was developed by the Australian Department of Defense (Hendy et al., 1984) for use with the RAAF Airtrainer CT-4A cockpit. The development of this program was based on the concept of fitting a given percentage of individuals for which adequate anthropometric data existed, rather than using the conventional approach based on pooled anthropometric data. For this reason, the simple 2-D model should not be used to define dynamic reach envelopes or volumetric relationships.

The SAMMIE (system for aiding man-machine interaction and evaluation) model (Bonney, 1979; Kingsley et al., 1981) includes the anthropometric tables necessary to generate a three-dimensional image of a user. This system has been used as a design and evaluation tool. Simpler and less sophisticated models are the computerized accommodated percentage evaluation (CAPE) model (Bittner, 1975) and the crewstation assessment of reach (CAR) (Edwards et al., 1976).

The COMBIMAN (Kroemer, 1972; McDaniel, 1976; Korna and McDaniel, 1985) system was developed to assist in the design and analysis of crew stations. This model is based on a 35-link skeletal system. The CREW CHIEF (Korna et al., 1988) simulation package is another program developed to analyze the interactions of the man-model's physical characteristics and capabilities with the workstation configuration. CREW CHIEF operates interactively with the CADAM* (computer aided design and manufacturing) package. This package was primarily designed to analyze the maintainability of designs, analyze the interaction of a maintenance technician with a system, and enable the user to evaluate limitations and capabilities in the areas of physical accessibility, strength, and visibility.

The main problem with the above packages has been the task specificity, specialized computer hardware requirements, and the level of user friendliness. Mannequin™ is a simpler yet powerful system ideal for man-machine systems design. The package is designed to run on the most popular type of computers, personal computers. The 3-D capabilities of Mannequin can be utilized to produce working drawings of workplaces. The anthropometric databases built into the package allow the user to evaluate and design "machines" with great ease. An example of a "machine" design in the presence of a human operator is shown in Fig. 1.10.

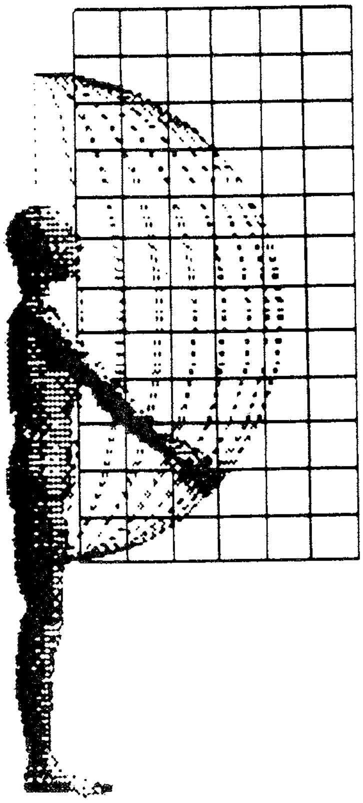


FIGURE 1.8 Standing reach envelope (one arm) for 5th percentile male. (*Courtesy of HumanCad Inc., Melville, New York.*)

TASK ANALYSIS

Overview. The most important methodology in ergonomic assessment is task analysis. A task may be described as one which comprises a set of human actions ultimately resulting in the output of the system. The term task analysis has had many meanings in this century. Task analysis in an ergonomic context refers to the process of identifying and describing subtasks and analyzing these for the successful performance of the job. The smallest subtask to be used in an ergonomic analysis is one which has no fixed boundaries but one which the ergonomists determine based on the job at hand. The elements of a task analysis are

1. Task description
2. Requirement specification
3. Analysis
4. Evaluation

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*CADAM is a registered trademark of CADAM, Inc., 1935 N. Buena Vista Street, Burbank, Calif., 91504.

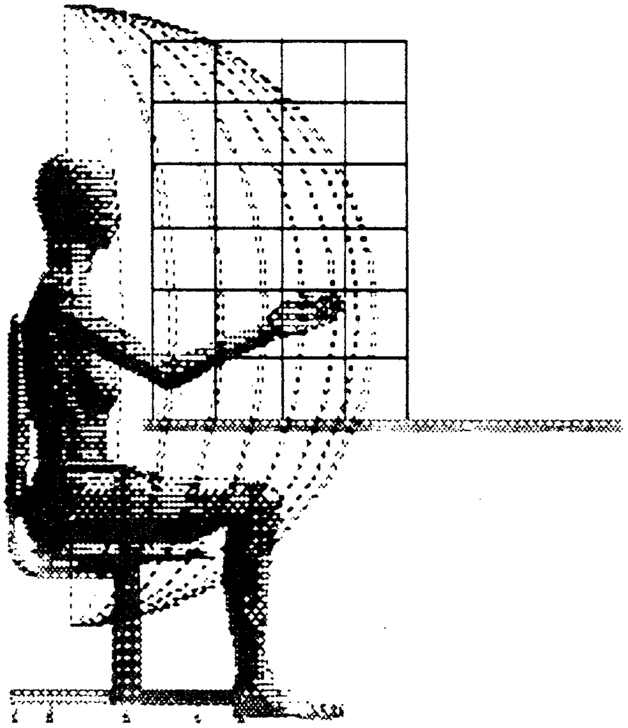


FIGURE 1.9 Forward reach envelope of seated 5th percentile female. (*Courtesy of HumanCad Inc., Melville, New York.*)

The requirement specification of the job entails measuring the four primary components of each subtask, namely,

1. Force
2. Frequency
3. Posture
4. Environment

The following sections describe the different techniques used in current ergonomic practice.

Force Measurement. In the study of biomechanics, force plays an important role. Force measurement is done through the use of force transducers. The simplest force transducers are mechanical, and these include spring dynamometers and cable tensiometers. Isokinetic dynamometers are another kind used for obtaining back strength. Electronic transducers, on the other hand, are used when accuracy is important (Fig. 1.11).

The most common types of electronic transducers are the strain gauge, piezoelectric transducers, and linear variable differential transformer (Eastman Kodak Company, 1983). For electronic transducers the strain induced as the result of the force (stress) varies the electrical characteristics and hence the voltage. This voltage can then be calibrated to indicate the force. When multiple force transducers are used, such transducers are referred to as a force plate or force platform (Morgan and Bhattacharya, 1984). Force plates are used to study ground reaction forces that resist the feet. Another application is for the measurement pressure between buttocks and seat surfaces when seated (*Autoweek*, 1990).

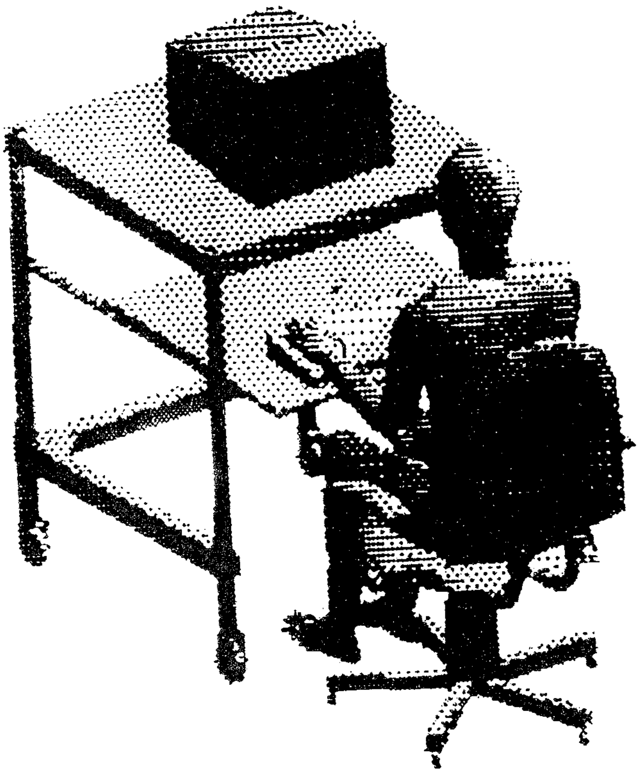


FIGURE 1.10 Human-machine design with HumanCad. (*Courtesy of HumanCad Inc., Melville, New York.*)

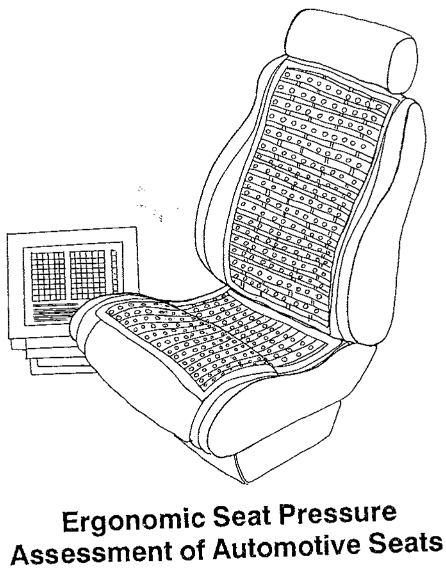
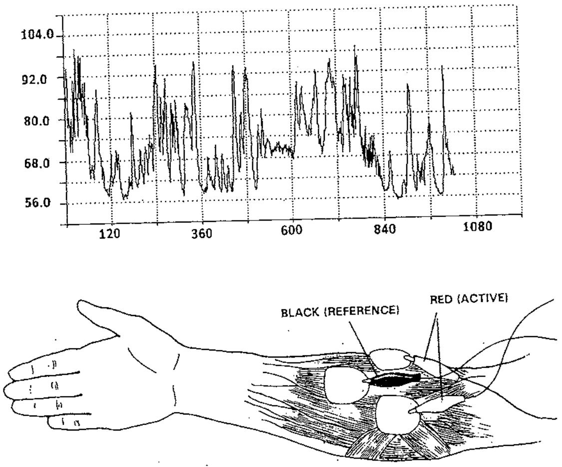


FIGURE 1.11 Flexible circuit force measurement system.

Muscle Strength. Mechanical force transducers are used to measure isometric strength of human muscles. However, the most commonly used technique for measuring muscle load is electromyography (EMG). EMG is based on the electromechanical coupling of muscles and provides a means of quantifying the muscular strain. Rapidly fluctuating differences of potential within the tissues and across the skin are created when muscles are activated by signals from the nerves. A record of the potential changes (ranging from a few microvolts to a few millivolts) between two electrodes placed on the skin surface or embedded in the tissues is called an electromyogram. The electrodes used for EMG are of three types: surface electrodes, needle electrodes, and fine-wire electrodes. The surface electrode is the most popular type. They consist of a disk which is placed over the muscle being studied. The needle electrode is inserted into the muscle of interest, and even though this results in an invasive procedure the experimenter has better control in isolating the muscle. The fine-wire electrode methodology is similar to that of needle electrodes. The electrode here comprises two fine wires which are inserted into the muscle studied with the use of a needle. The needle is removed, leaving only the fine wires inside the muscle.

In ergonomic assessments, surface electrodes are common because of their ease of use and attachment. With surface electromyography different electrode arrangements are possible. Some are the unipolar, bipolar, tripolar, and concentric annular. The tripolar arrangement, for example, is comprised of three evenly spaced electrodes in a linear array. The potentials of the two outer electrodes are averaged, and the difference to the central electrode potential is recorded.

There has been disagreement in the exact relationship between the electrical signal and the tension generated on the muscle. Bigland and Lippold (1954) reported a linear relationship while Bouisset (1973) reported a nonlinear relationship under different experimental conditions. However, there is general agreement that a linear relationship exists in static conditions while a strong correlation is present with dynamic conditions. An example of an electromyogram is shown in Fig. 1.12. The standards for reporting EMG data are given by Winter et al. (1979).



Electrode Placement for Flexor and Extensor Muscles

FIGURE 1.12 Electrode placement and EMG of flexor and extensor muscles during load carrying.

EMG signals can be processed in many different ways. If overall muscle force is of interest, the signal must be integrated. Such integration is possible through the use of the peak value, the rectified average value, the root-mean-square (rms) value, the number of level crossings (for example, zero crossings) per unit time, the number of peaks per unit time, and so on. Through the use of spectral analysis techniques, center or median frequencies may be obtained. Chaffin (1973), Petrofsky (1979), and others have reported how EMG spectral density can be used to determine muscle fatigue. When muscular fatigue is present, the amplitude of the higher-frequency components decreases while the amplitude of the low-frequency components increases. The mean power frequency is a useful measure for detecting this change.

Prior to the processing of the signals it is customary to normalize the signals. One such normalization is done with respect to each subject's maximum EMG activity. The maximum amount of force that a muscle can exert is known as the maximum voluntary contraction (MVC). When the EMG activity is expressed as a percentage of the maximum

EMG activity, the measure is referred to as the percent maximum voluntary contraction (% MVC). Muscular strength is normally expressed in these units. As the % MVC approaches 100, the muscle is working near its maximum strength and can hold such force for only a few seconds. The muscular force and the maximum endurance time (MET) relationship was first developed by Rohmert (Fig. 1.13).

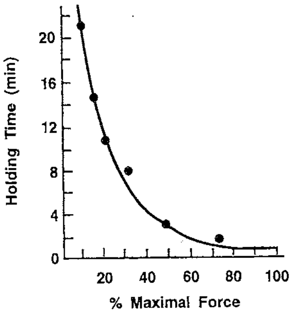


FIGURE 1.13 Force-time relationship for pull condition (Rohmert's 1968 curve). (*J. R. Wilson and N. C. Corlett, 1990.*)

Another normalization procedure is with respect to the resting EMG activity. An alternative measure is the relative muscle activity defined as follows:

$$\text{Relative activity} = \frac{\text{recorded EMG} - \text{resting EMG}}{\text{maximum EMG} - \text{resting EMG}}$$

In the normalization it is important that the correct posture be used. If the EMG signals of the wrist are being evaluated, the grip type and posture are both important. To take into account extreme variabilities in a work cycle Silverstein et al. (1986) have proposed the "adjusted force" measure defined as

$$\text{Adjusted force} = (\text{variance/mean force}) + \text{mean force}$$

Based on this measurement they concluded that the combination of high force and high repetitiveness (frequency) increases the risk of cumulative trauma diseases as opposed to any other combination of force and frequency.

Posture Measurement. Researchers have used many methods for posture measurement. These can be categorized as

1. Direct measurement techniques
2. Indirect measurement techniques

Posture measuring instruments may be mechanical, eletromechanical, or optical. Electrogoniometers are frequently used to quantify joint motion. The criteria to bear in mind with the use of any angle measurement technique are

1. Accuracy
2. Compactness
3. Ease of use
4. Unconstrained movement of joint

The electrogoniometer is attached to the limbs of the body with the axis of rotation of the goniometer coinciding with the axis of rotation of the limb. When a constant voltage source is applied between the ends of the goniometer, the resistance of the potentiometer is a function of the joint angle. The electrogoniometer can thus be calibrated to measure the angle directly.

Researchers have developed many methods to measure the motion of the trunk. O'Brien and Paradise (1976) used strain gauges on the lower back to measure trunk flexion. Nordin et al. (1986) used a flexion analyzer for trunk movements in the sagittal plane. This instrument consisted of a pendular potentiometer, a five-level analog-to-digital converter, nine digital registers, and the appropriate control circuits. One of the drawbacks of this device is that the unit needs to be worn on the back of the subject studied.

The flexible curve method (Burton, 1986) is an inexpensive way to perform postural measurement. The disadvantage of this method, however, is that it is cumbersome and complex for many limb joints.

Optical instruments are based on imaging techniques such as cinematography, video recorders, multiple-exposure photographic techniques, or optoelectronic techniques. In cinematography, Cine or motion picture cameras are used. The most common and least expensive method that exists today is video recording. Another simple and economical approach is the multiple-exposure technique. Reflective markers placed on the body are tracked with a still camera with each illumination made using a strobe light. The resulting photograph shows a stick figure which is used for analysis. The disadvantage of this method is that it needs to be done in a dark room and where a strobe light will have no effect on the work performed.

One optoelectronic technique available today is the Selspot system (Selcom Inc., Sweden). This system uses infrared light sources, light-emitting diodes, or laser light sources. The light sources are attached to the body and are then sensed by the Selspot cameras. The camera output can be computer processed for precise position information. The capability of obtaining speed, acceleration, and rotation of limbs makes this a powerful method for motion analysis.

The Vicon system (Oxford Medical Systems, U.K.) is another system used for postural measurement. In the Vicon system, infrared retroreflective markers are detected by video cameras. From this point detection, 3-D coordinate files for body marker positions are produced.

Another system, the Spectron miniature inclinometer, uses single-axis electrolytic potentiometers. The output voltage of the unit is proportional to the angle from the vertical. Biplane inclinometers have been used by many researchers for head and spinal postures (Nordin, 1982; Weber et al., 1986). These instruments use miniature load cells mounted on two tumbling weights. The resultant force is then proportional to the angle of the tumbling weight with respect to the vertical.

The goal of these measurement systems is to quantify the position of the body in space. The analysis which follows this quantification is either observational, that is, intuitive, or biomechanical. There is a trade-off between one activity to accurately specify position and the time and encumbrance necessary to achieve this. As a result, most workplace posture measurement systems have given way to the simplicity and lower cost of video recording.

Environment. The elements of concern in an ergonomic analysis related to environment are:

1. Noise
2. Illumination
3. Motion and vibration
4. Climate

Noise is measured in decibels. In the decibel scale, sound pressure (p) is expressed as a fraction of a reference pressure (p_{ref}) value. Sound pressure level (SPL) in decibels = 20 log (p/p_{ref}). In the measurement of sound the two important parameters are the sound pressure level and the frequency. The sound pressure level is usually measured with the use of a sound-level meter. Sound-level meters built to American National Standards Institute (ANSI) standards possess different weighting scales for the various frequencies. These scales are designated as A, B, or C. The D scale is used primarily as a measure of aircraft noise and is not of importance here. The C scale weights all frequencies equally. The Occupational Safety and Health Administration (OSHA) standards are based primarily on the A scale. The sound levels and their relation to exposure duration for human beings are shown in Fig. 1.14.

A more detailed description of noise measurement may be found in Jones and Chapman (1984). When the sound pressure levels cannot be reduced below "safe" levels it is necessary that the operators in such environments use ear protection. The reusable types of

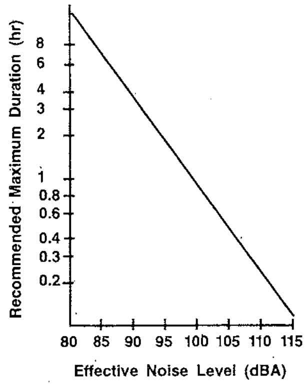


FIGURE 1.14 Noise level and maximum recommended exposure duration. (*Eastman Kodak Company, 1983.*)

devices are earplugs and earmuffs. Disposable forms such as cotton are used sometimes. Harris (1979) provides other means of reducing the environmental noise encountered in industry.

Illumination is the measure of light falling on a surface. In the SI system it is measured in lux. Illumination is also measured in footcandles (fc). Luminance is the amount of light emitted in a given direction by a luminous source or by an illuminated surface. In the SI system luminance is measured in candelas per square meter (cd/m^2). It is also expressed in footlamberts (ftL). A photometer is used to measure the amount of luminance. Many authors have reported studies where strong correlations exist between the level of lighting and operator behavior. The reader is referred to the IES Lighting Handbook (1982, 1983) and Kaufman and Haynes (1981a, 1981b) for a more comprehensive analysis.

Vibration on the human system can be whole-body or segmental (for example, hand-arm). ISO (1974, 1978, 1985) gives the effects of vibration duration on human comfort. The ISO (1979, 1984, 1988) provides guidelines and principles to measure the vibration transmitted to the hand.

The modern measurement of vibration involves the conversion of mechanical energy to electrical energy. The most common types of transducer used for vibration measurement are piezoresistive accelerometers (for whole-body vibration) and piezoelectric accelerometers (for hand-transmitted vibration). Accelerometers produce electrical signals proportional to the acceleration present.

The electrical signals from the transducer may be instantaneously processed or else stored on a tape recorder or computer for later analysis. The two common types of analysis are amplitude composition and frequency composition. Many measures have been used to quantify the amount of vibration, for example, mean, standard deviation, root-mean-square, skewness, kurtosis, root-mean-quad, vibration dose value, estimated vibration dose value, peak, crest factor, and so on. For vibrations which change with time the rms value may not be an appropriate measure. Under such circumstances the vibration dose value will be a more meaningful measure.

For whole-body vibration this measure will give a better indication of the total severity of the vibration magnitude. The vibration dose value (VDV) has been defined by

$$\frac{[T_s \Sigma x^4(i)]^{0.25}}{N}$$

where T_s = vibration duration
N = total number of samples with frequency f_s (samples per second)
$x(i)$ = sample data values where i = 1 to N

The estimated vibration dose value (*eVDV*) is defined by

$$[(1.4R)^4 \times T_s]^{0.25}$$

where

$$R = \text{root-mean-square value} = \frac{[\Sigma x^2(i)]^{0.5}}{N}$$

The simple measure when the peak value and the rms value are not appropriate is the crest factor, which is defined as

$$\text{Crest factor} = \text{peak value/rms value}$$

The crest factor provides an indication of the shape of the wave studied. For example, in sinusoidal vibration the crest factor is $(2)^{0.5}$, or 1.414.

It is important that vibration measurements be done at the human-machine interface. Measurements carried out at any other point will not represent a true picture of the value, since damping occurs with almost any surface. In an automobile seat, for example, if vibration is important, the measurement ought to be made between buttock and seat surface and not at the floor of the vehicle or at the cardiac region of the human. In every case the two important elements are mounting the transducer at the correct location and whether the characteristics of the transducer are influenced by the vibration being measured.

When measurements have to be made at such interfaces, it is necessary that the transducers be placed at the interface itself. However, with all such measurements it must be ensured that the transducer does not affect the human body or the "machine" surface characteristics. SAE (1974) has defined a device suitable for many such measurements. However, a few limitations such as the inability to mount existing accelerometer designs exist. The International Organization for Standardization (ISO) has provided many important characteristics and measurement procedures for vibration (1979, 1984, 1988). Whitham and Griffin (1977) provide a sufficient size platform for mounting using the "seat interface for transducers indicating acceleration received (SIT-BAR). This device has a contoured lower surface and a flat upper surface such that the transducer will compress similar to the human buttocks. Lawther and Griffin (1980) have described ways in which acceleration may be estimated using six translational accelerometers.

Climate. The factors in the area of climate affecting human performance are temperature, air velocity, and humidity. The reader is referred to the numerous publications of the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) for more elaborate descriptions in this area (for example, ASHRAE, 1981).

Analysis and Evaluation. Methodology in the area of analysis and evaluation is very limited. The effects of force and frequency on hand disorders were first quantified by Silverstein et al. in 1986. The authors concluded that a high odds ratio of cumulative trauma disorders were present with high force (in this case an adjusted hand force greater than 6 kg was considered high) and high repetition. A job with a cycle time of less than 30 seconds or a job where 50 percent of the time the operator performed the same fundamental cycle was categorized as high repetition. Drury (1987) used the measure *daily damaging wrist motions* to quantify wrist damage potential in industrial tasks. This measure was defined as the total frequency of the damaging wrist motions over one day. The damaging wrist motions were ones which exceeded 10 percent of the range of joint motion. Drury identified four zones for movement. Zone 0 was categorized as one with no exposure (up to 10 percent of range of motion), zone 1 as low exposure (10 to 25 percent of range), zone 2 as moderate exposure (25 to 50 percent of range), and zone 3 as severe exposure (more than 50 percent of range).

Both the above studies have primarily concentrated on two variables, either force and frequency or posture and frequency. However, in manual work force, frequency and posture are important. In redesign of workplaces it is necessary to eliminate all hazardous tasks. However, because of cost and technology constraints it may not be physically feasible to redesign all components of a job. In such cases a quantitative measure of value would be the force-frequency-posture index (FFPI) defined for each subtask, i (SFFPI_i) as

$$\text{SFFPI}_i = (\text{force} \times \text{frequency} \times \text{zone number})$$

and the FFPI index for job (JFFPI) as

$$\text{JFFPI} = \text{summation over all subtasks } (\text{SFFPI}_i)$$

The FFPI values and the biomechanical analysis can then be used to compare the job requirement specification with the operator capabilities. Redesigns of workplaces are based on this comparison such that the job demands are less than or equal to the operator capabilities.

BIOMECHANICS

Definition. Biomechanics is an interdisciplinary field that fuses physics and engineering and medicine to analyze the forces and moments acting upon the body joints during the performance of daily activities, whether at rest or while in motion. The scientific basis for biomechanics is drawn from the disciplines of statics, dynamics, engineering anthropometry, kinesiology, and bioinstrumentation. Biomechanics is the key tool for quantitative ergonomic assessments.

Biomechanics deals with the areas of biostatics (the study of the forces acting on bodies at rest), biodynamics (the fundamental laws describing the kinematics and kinetics of body movement), and occupational biomechanics (the application of biomechanical principles toward improving working conditions). This section deals primarily with the concepts of occupational biomechanics and its role in the broader field of ergonomics. In essence, the human body is a kinematic linkage system. When a load is applied on the hands, reactive forces and moments are produced throughout the body joints in the linkage system.

Statics and Dynamics. Mechanics is an applied science which aims to explain and predict physical phenomena and lay the foundations for most engineering applications. The basic concepts used are those of space, time, mass, and force. The concepts of space and time are used to define an event, specifying the location where and the instance when the event occurred. The concept of mass is used to characterize and compare bodies on the basis of certain fundamental mechanical experiments. The concept of force represents the action of one body on another. Statics deals with bodies at rest while dynamics deals with bodies in motion.

The forces acting on bodies may be separated into two categories: (1) external forces and (2) internal forces. External forces represent the action of other bodies on the body under consideration, either causing it to move or assuring that it remains at rest. Internal forces are those which hold the body together. Forces are vector quantities characterized by magnitude, direction, line of action, and point of application. The method of analysis is usually to draw a system of forces acting upon a body. This is commonly referred to as the free-body diagram.

The state of equilibrium of a body is determined from this free-body diagram. This means that the additive effect of all external forces acting on a body and the combined moment effects of the forces should be equal to zero.

For static conditions, the reactive force produced about a certain body joint to prevent motion can be calculated through the additive effects of the external load applied and the forces due to the weight of appropriate body segments. The reactive moment produced on the body joint can be determined in a similar manner, this time considering not only the forces but also the perpendicular distances of these forces (lever arm) from the body joint. Figure 1.15 shows a simplified example of the reactive force and moment produced about the elbow joint as a load is applied on the hands.

For dynamic conditions, inertial forces, in addition to gravity, act on a body segment as it is pivoted about a joint center. These inertial forces are the combined effects of the tangential force (tangent to the arc of motion) at the body segment's center of mass and the centrifugal force (perpendicular to the arc of motion). Aside from the mass of the body segment, the distance from the joint center to the body segment center of mass, the instantaneous angular velocity of the body segment and the instantaneous angular acceleration of the body segment need to be defined to calculate the tangential and the centrifugal forces. Please refer to Fig. 1.16 for an example of how these forces are calculated.

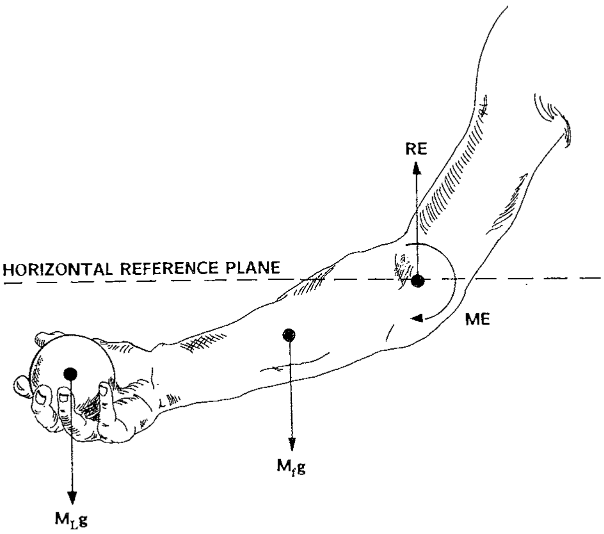


FIGURE 1.15 Reactive force and moment at the elbow joint.

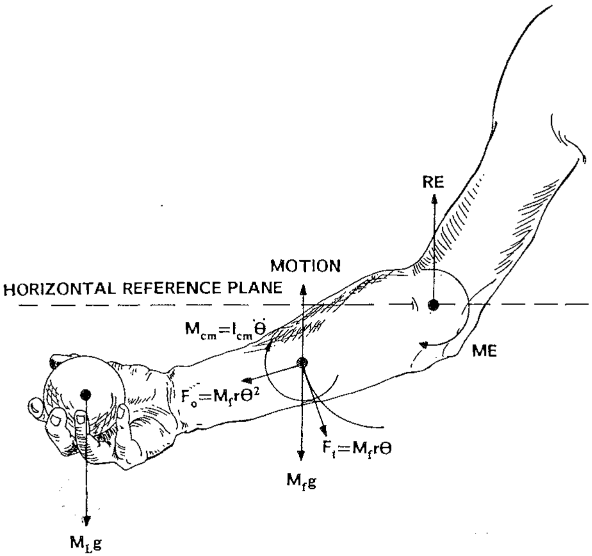


FIGURE 1.16 Calculation of tangential and centrifugal forces.

The NIOSH Work Practice Guide to Manual Lifting. The National Institute for Occupational Safety and Health publication entitled *Work Practices Guide to Manual Lifting* (NIOSH, 1981) offers specific guidelines for evaluating human lifting capabilities intended for general industry use. The guidelines were meant to be applicable only to smooth, two-handed, symmetric lifting. It also calls for unrestricted posture, good handles on a moderately wide object, good environmental conditions, and no other significant manual materials handling tasks being performed during the course of the working day. The guide defines two limits: the action limit (AL) and the maximum permissible limit (MPL). The range between these limits is defined to consider the large variability in the general U.S. working population.

The action limit (AL) has been established as the maximum weight that produces 3400 N (approximately 750 lb) of compressive force on the L5/S1 disk, requires a metabolic load of 3.5 kcal per minute for a healthy young female, and can be sustained by over 99 percent of the males and 75 percent of the females. Epidemiological data have also indicated an increased risk of injury on lifting jobs exceeding the AL.

The maximum permissible limit (MPL) has been defined as three times the value of the action limit. Lifting at this limit produces 6400 N (approximately 1410 lb) of compressive force on the L5/S1 disk, requires a metabolic load of 5.0 kcal per minute for a healthy young male, and can be performed by only 25 percent of the males and less than 1 percent of the females. Epidemiological data also indicated that injury and severity rates are significantly higher for most workers who perform lifting jobs above the MPL.

Three ranges of stresses caused by lifting jobs have been defined using the AL and MPL. Lifting below the AL is presumed to create nominal stress and is of little risk to most people. Lifting above the MPL is considered unacceptable, and engineering controls (such as the use of hoists and similar materials handling mechanisms) should be implemented to eliminate the stresses produced by the lifting conditions. Lifting between the AL and MPL is also considered unacceptable without the implementation of engineering and/or administrative controls. Administrative controls include proper employee selection (functional capacity testing), employee training programs (proper work habits and overall fitness training), and job redesign.

The equations to determine AL and MPL (both in N) are as follows:

$$\mathrm{AL} = 392 \times (15/H) \times [1 - (0.004 \times |V - 75|)] \times [0.7 + (7.5/D)] \times [1 - (F/F_{\max})]$$

$$\mathrm{MPL} = 3 \times \mathrm{AL}$$

where H = the horizontal distance between the load center of mass at the origin of the lift and the midpoint between the ankles. Values of H range between 15 and 80 cm (6 to 31.5 in).

V = the vertical distance from the surface where the object to be lifted is placed to the load center of mass at the origin of lift. Values of V range from 0 to 175 cm (0 to 70 in).

D = the vertical distance of travel of the load. Values of D range from 25 to $(200 - V)$ cm [10 to $(80 - V)$ in]. If the vertical distance of travel is less than 25 cm, then 25 cm is used as the minimum value.

F = the average frequency of lifting. Values for F range from a minimum of 0.2 lift per minute (one lift every 5 minutes) to a maximum value $F_{\max}$ defined by the duration of the lifting task (1 hour or 8 hours). The values for $F_{\max}$ are as follows:

$F_{\max}$ = 12 lifts per minute if $V < 75$ cm and task duration = 8 hours

$F_{\max}$ = 18 lifts per minute if $V > 75$ cm and task duration = 1 hour

$F_{\max}$ = 15 lifts per minute if $V > 75$ cm and task duration = 8 hours
or if $V < 75$ cm and task duration = 1 hour

It should be noted that as of this writing, the NIOSH guidelines are under review. The effects of twisting while lifting (asymmetric lifting) are currently being considered.

Computation of Dynamic Forces and Torques on the Human Body. The NIOSH Guide applies only for calculating the spinal compressive force during symmetrical lifting in the sagittal plane. To describe and evaluate manual work, it is often necessary not only to analyze the reactive forces on the various body joints but also to compare load moments at these joints with population capabilities. In general, the forces acting on the hands are viewed as vector quantities acting separately on each hand. Biomechanical models then predict the moment load on each body joint.

Since the human body may be considered as a multilinkage system, a sequential set of analysis is performed to calculate the reactive forces and moments about a body joint. Most whole body biomechanical models divide the human body into seven links: hand and forearm, upper arm, shoulder to L5/S1 disk, shoulder to hip, L5/S1 disk to hip, thigh, and lower leg. Usually the calculations begin with the forearm-hand link and continue until reaching the stationary link (in most lifting tasks, the analysis ends with the foot). Hence the reactive force and moment about the elbow joint are added to the other forces and torques acting on the shoulder joint, and the reactive force and moment about the shoulder are added to the other forces and torques acting on the L5/S1 disk, and so on.

Recently, a two-dimensional dynamic biomechanical model (BackSoft®) to analyze the stresses imposed on the body during workplace tasks has been developed. Centers of gravity are calculated for the hand and forearm link, the upper arm, the torso, the head, the pelvis, the thighs, and the lower legs. Link lengths and center of gravity weights and locations are calculated as a percent of the height and weight of the person being evaluated. The compressive force produced on the L5/S1 disk is compared with the value of 3400 N [which is the compressive force produced on the L5/S1 disk when lifting at the action limit (AL) level] to determine whether administrative or engineering controls are required. The predicted strength of each joint is calculated as a function of the enclosed angle of the joint to determine the percent of the population capable of performing the task being analyzed.

Because of the complications of the calculations, certain assumptions were made in the calculation of body motion and torques for the BackSoft® program. These include

1. Constant angular velocity for each limb
2. Fixed center of gravity for each limb
3. Limb rotation about a joint in the third dimension is neglected
4. All forces and torques act at the joint center of rotation
5. Forces are applied by both hands
6. Both feet are flat on the ground in a similar position

The sign convention is: positive X axis to the right, positive Y axis upward, and positive moment counterclockwise. Consider a person lifting a load from the floor to a shelf. The free-body diagram of the linkage system is presented in Fig. 1.17. For purposes of simplicity, only the equations for calculating the reactive forces and moments about the elbow

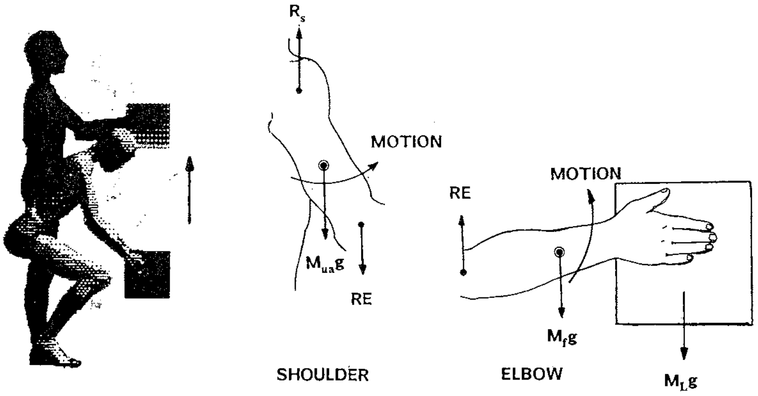


FIGURE 1.17 Free-body diagram of the linkage system.

and shoulder joints will be shown. The instantaneous reactive force on the elbow joint is computed by adding the component effects of the load and the gravity effects of the segment weights at this joint. The moment about the elbow joint is computed by adding the segment rotational moment of inertia, the linear acceleration effects, and the static effects due to gravity. The reactive forces and moment about the elbow are then calculated as follows:

$$F_{Ex} = 0$$

$$m_L a_{Lx} + m_f a_{fx} - R_{Ex} = 0$$

$$R_{Ex} = m_L a_{Lx} + m_f a_{fx}$$

$$F_{Ey} = 0$$

$$m_L g + m_L a_{Ly} + m_f a_{fy} - R_{Ey} = 0$$

$$R_{Ey} = m_L g + m_L a_{Ly} + m_f a_{fy}$$

$$M_E = 0$$

$$\begin{aligned} M_E - D_{EL} m_L g(\cos \beta_E) - D_{EL} m_L a_{Ly}(\cos \beta_E) - D_{EL} m_L a_{Lx}(\sin \beta_E) \\ - D_{Ef} m_f a_{fy}(\cos \beta_E) - D_{Ef} m_f a_{fx}(\sin \beta_E) - I_f \ddot{a}_f = 0 \end{aligned}$$

$$\begin{aligned} M_E = D_{EL} m_L g(\cos \beta_E) + D_{EL} m_L a_{Ly}(\cos \beta_E) + D_{EL} m_L a_{Lx}(\sin \beta_E) \\ + D_{Ef} m_f a_{fy}(\cos \beta_E) + D_{Ef} m_f a_{fx}(\sin \beta_E) + I_f \ddot{a}_f \end{aligned}$$

where R_{Ex} = force at the elbow joint in the x direction
R_{Ey} = reactive force at the elbow joint in the y direction
m_L = mass of load
g = acceleration due to gravity
a_{Lx} = instantaneous acceleration of the load in the x direction
a_{Ly} = instantaneous acceleration of the load in the y direction
m_f = mass of the forearm
a_{fx} = instantaneous acceleration of the forearm in the x direction at the center of mass
a_{fy} = instantaneous acceleration of the forearm in the y direction at the center of mass
M_E = reactive moment about the elbow joint
D_{EL} = distance from elbow joint to center of mass of the load
D_{Ef} = distance from elbow joint to center of mass of the forearm
β_E = forearm angle from the horizontal axis
I_f = moment of inertia of the forearm about the axis through the center of mass
$\ddot{a}_f$ = angular acceleration of the forearm about the elbow

The instantaneous reactive forces and moments on the shoulder joint are computed byadding the reactive forces and moment about the elbow joint and the gravity and moment of inertia effects of the upper arm at this joint. The reactive forces and moment are then calculated as follows:

$$F_{Sx} = 0$$

$$m_{ua} g + m_{ua} a_{uax} + R_{Ex} - R_{Sx} = 0$$

$$R_{Sx} = m_{ua} g + m_{ua} a_{uax} + R_{Ex}$$

$$F_{Sy} = 0$$

$$m_{ua} g + m_{ua} a_{uay} + R_{Ey} - R_{Sy} = 0$$

$$R_{Sy} = m_{ua}\,g + m_{ua}a_{uay} + R_{Ey}$$

$$M_S = 0$$

$$M_S - M_E - I_{ua}\ddot{a}_{ua} - D_{Sua}m_{ua}a_{uay}(\cos \beta_S) - D_{Sua}m_{ua}a_{uax}(\sin \beta_S) = 0$$

$$M_S = M_E + I_{ua}\ddot{a}_{ua} + D_{Sua}m_{ua}a_{uay}(\cos \beta_S) + D_{Sua}m_{ua}a_{uax}(\sin \beta_S)$$

where R_{Sx} = reactive force at the shoulder joint in the x direction
R_{Sy} = reactive force at the shoulder joint in the y direction
R_{Ex} = reactive force at the elbow joint in the x direction
R_{Ey} = reactive force at the elbow joint in the y direction
m_{ua} = mass of the upper arm
g = acceleration due to gravity
a_{uax} = instantaneous acceleration of the upper arm in the x direction at the center of mass
a_{uay} = instantaneous acceleration of the upper arm in the y direction at the center of mass
M_S = reactive moment about the shoulder joint
M_E = reactive moment about the elbow joint
I_{ua} = moment of inertia of the upper arm about the axis through the center of mass
$\ddot{a}_{ua}$ = angular acceleration of the upper arm about the shoulder
D_{Sua} = distance from shoulder joint to center of mass of the upper arm
β_S = upper arm angle from the horizontal axis

The reactive forces and moments about the other body joints (for example, L5/S1 disk, hips, knees) are calculated in a similar manner. These are computed by adding the effects of the body segment mass and accelerations to the corresponding reactive forces and moments about the preceding body joint.

Reducing Musculoskeletal Stress through Workplace Redesign. When redesigning working conditions, several factors need to be considered. These include the following:

1. Amount of force applied to manipulate the loads being handled
2. Size, shape, stability, and center of mass of the load
3. Design of handles, if any
4. Workplace layout
5. Cycle times and durations of the tasks
6. Environmental conditions
7. Personal protective devices and other work habits or methods

One of the primary factors included in the calculation of the NIOSH recommended action and maximum permissible limits is the horizontal distance between the center of mass of the load and person performing the manual materials handling task. In general, a smaller horizontal distance results in lower reactive forces and moments, particularly about the L5/S1 disk. Hence the amount of bending down or forward leaning should be minimized as much as possible. Also, any obstructions between the worker and the load should be eliminated. A common way of minimizing this horizontal distance is through the use of roller conveyors, gravity-fed slides, titled stock bins, and similar devices which bring the loads to the person performing the task instead of the person's having to reach for the load.

Another factor considered in the calculation of the NIOSH action and maximum permissible limits is the vertical location of the center of mass of the load with respect to the floor surface. Research studies have indicated that the lifting limits are 30 percent lower for lifting below the knuckle height than for lifting at knuckle height. Recently, the use of spring-loaded pallets or vertically adjusting support tables has been implemented to allow the person to maintain a more erect posture regardless of how many more loads are left on the pallet or table.

WORK METABOLISM

Principles of Energy Conversion in the Body. The *energy expenditure* of the human body can be determined from measurements on the respiratory system. The cells of the body get most of their energy from reactions that require oxygen, and finally eliminate carbon dioxide. Some basic definitions about the respiratory process follow (Astrand and Rodahl, 1986; Kroemer, Kroemer, and Kroemer-Elbert, 1986).

The *respiratory system* is made up of all the structures that move air in and out of the lungs. Oxygen in the air is taken into the bloodstream and carbon dioxide and water are removed from the body. The volume of air depends on the inspiratory and expiratory muscle activity. When the air from the lungs is forcibly expelled as much as possible, the lungs still contain a residual volume of approximately 1000 mL. A forced maximum inspiration of air adds a volume of about 5000 mL known as the vital capacity, a measure of the lung's fitness. During normal, quiet breathing a tidal volume of approximately 500 mL is moved in and out. The pulmonary ventilation is described by the minute volume and is calculated by multiplying the tidal volume by the frequency of breathing.

The *oxygen intake* V_{O_2} is the volume of oxygen absorbed per minute from the inspired air. At rest the value is about 0.2 liter/min. The heart rate is the number of times the heart's ventricles contract per minute. The resting rate is about 60 to 70 beats per minute. The pulse rate is an estimate of the heart rate.

The *metabolic processes* in the body release the energy contained in the nutrients that are taken in. The output is in the form of energy to maintain the body, as work and as waste.

The *basal metabolism* is the minimum amount of energy required for the body to function. It is measured under controlled conditions and is approximately equal to 4.9 kJ/min for a 70-kg person. The resting metabolism is measured at the beginning of the day with the subject resting. The resting metabolism is 10 to 15 percent higher than the basal metabolism. It is different from the working metabolism, which is the increase in the metabolic level between the resting level and the working level.

Metabolic Activity During the Work Cycle. Figure 1.18 shows how the oxygen uptake increases very little at the start of work. After this, the oxygen intake rises rapidly and then reaches a steady state at the level required by the body to perform the work. Thus at the start of the work the oxygen demand is more than the amount available, and an "oxygen debt" is incurred. The extent of the deficit depends on the intensity of the work. At the cessation of work, the oxygen demand drops rapidly and then tapers off gradually. The "oxygen debt" is repaid at this stage, with about double the amount as the deficit.

The reason for the slow increase in the oxygen demand at the start of work is that it takes time to increase the flow of oxygen-rich blood to the body. The metabolic processes at this stage are anaerobic, and lactic acid, a waste product, is produced; the oxygen present in the muscles is insufficient for the work level. When the work is over a prolonged period the oxygen supply matches the cardiac requirements and a steady state that can be maintained is reached. The workload at this stage should not exceed 50 percent of the maximal oxygen uptake.

When the work level requires more than half the maximal oxygen uptake, anaerobic processes are needed again. These result in lactic acid accumulation, and fatigue. To restore a balance between oxygen supply and demand, rest pauses can be inserted in the work period. Figure 1.19 shows the effect of the rest periods on the metabolic recovery.

Measurement of Energy Expenditure

Energy Expenditure Tables. Table 1.9 shows the energy expenditures for different

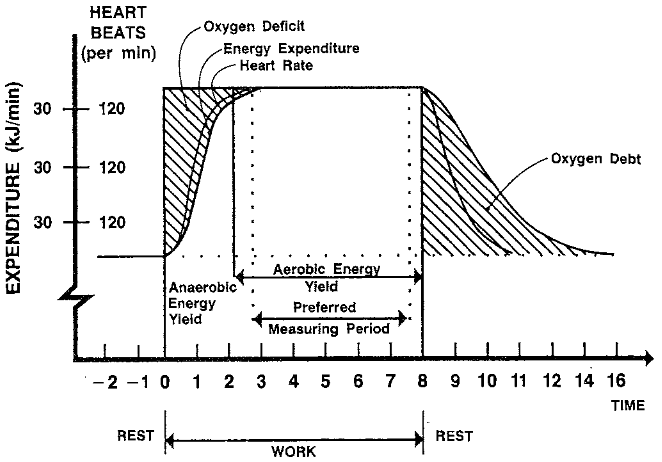


FIGURE 1.18 Energy expenditure during the work cycle. (*Kroemer et al., 1986.*)

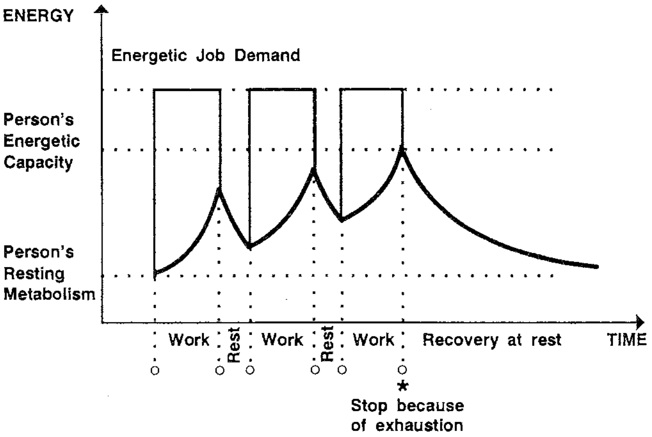


FIGURE 1.19 Effect of rest periods on metabolic recovery. (*Kroemer et al., 1986.*)

grades of work, and Table 1.10 for some selected activities. The energy determined by this method is an approximation, since the actual energy depends on the exact task, the fitness and skill of the individual, and the pace of work. The values from the table should be applied only to the time when the specific task is being performed.

Oxygen Consumption Method. The oxygen intake during work can be measured and used to estimate the energy expenditure. This method of estimation should be used when the levels of effort vary over the duration of the task. Oxygen intake is determined by measuring the volume of expired air and computing its oxygen content. The volume of expired air is multiplied by the difference in oxygen content between the expired air and the inspired air. The oxygen consumption in liters per minute is multiplied by 4.9 to give the energy in kilocalories. Except when the level of work effort is high, there is a linear relationship between oxygen consumption and energy expenditure.

TABLE 1.9 Classification of Work According to Energy Expenditure and Heart Rate

	Range for Class of Activity	
Class of Activity	Total Energy kcal/min	Heart Rate beats/min
Resting, sitting	1.5	60-70
Very light work	1.6-2.5	65-75
Light work	2.5-5.0	75-100
Moderate work	5.0-7.5	100-125
Heavy work	7.5-10.0	125-150
Very heavy work	0.0-12.5	150-180
Unduly heavy work	over 12.5	180+

Heart Rate Method. The heart rate of an individual has a linear relationship to the oxygen intake (Kroemer et al., 1986). The heart rate can be used to estimate the workload if the relationship for an individual is known and if the general work conditions are similar. Figure 1.20 (Astrand and Rodahl, 1986) illustrates the relationship between heart rate and oxygen uptake. The measured maximal oxygen uptake is used to construct another parallel scale with the load expressed as a percentage of maximal aerobic power. The weighted mean of the heart rate is used to assess the approximate average oxygen uptake.

Analytical Methods. Garg (1976) proposed a set of regression equations to predict energy expenditure. The equations give the energy expenditure for lifting in three different postures—standing, stooping, and squatting, and for carrying loads. A job is first divided into its elemental subtasks and their individual energy requirements computed. The total energy expenditure for the job is determined by summing up the energy expenditure for all the subtasks.

Asfour's (1980) method also uses regression to develop a set of equations that predict the energy for lifting and lowering tasks. The equations apply to the sagittal plane and to twisting movements. Intaranont's (1983) regression model predicts the threshold for anaerobic work and capacity for lifting weights.

Psychophysical Methods. Psychophysical methods of measuring energy expenditure depend on one's perception of task effort. These are based on models of the relationship between a physical stimulus and the sensation of the stimulus. They were originally formulated by Weber (1834) and Fechner (1860). Weber's law states that the smallest change, or the just noticeable difference, that can be detected in a stimulus depends on the absolute magnitude of the stimulus. Fechner (1860) proposed a logarithmic relationship between the perceived magnitude of a stimulus and its absolute value.

Borg (1982) extended these laws to develop a scale of ratings of perceived exertion (RPE). The scale is shown in Table 1.11. The subject's perception of the intensity of the

TABLE 1.10 Average Energy Cost in kcal/min for Selected Activities

Body Position and Activity	Total Energy Cost (Kcal/min*) Typical	Total Energy Cost (Kcal/min*) Range
1. Heavy activity at fast to maximum pace.		10.0-20.0
2. Jogging, level, 4.5 mph	7.5	
3. Lifting, 44 lb., 10 cycles per minute:		
-floor to waist	8.2	
-floor to shoulder	10.8	
4. Reclining at rest	1.3	
5. Running, level, 7.5 mph	12.7	
6. Shovelling, 18 lb load 1 yd with 1 yd lift, 10 times per min.	8.0	
7. Sitting at ease:		
-light hand work (writing,typing)	1.7	1.6-1.8
-moderate hand and and arm work (drafting, light drill press, light assembly, tailoring)		
-light arm and leg work (driving car on open road, machine sewing)	2.8	2.5-3.2
-heavy hand and arm work (nailing, shaping stones, filing)	3.5	3.0-4.0
-moderate arm and leg work (local driving of truck or bus)	3.6	3.0-4.0
8. Standing at ease:		
-moderate trunk and arm work (nailing, filing, ironing)	3.7	3.0-4.0
-heavy arm and trunk work (hand sewing, chiselling)	6.0	4.0-8.0
9. Walking, casual (foreman, lecturing)	3.0	2.5-3.5
-moderate arm work (stock room, sweeping)	4.5	4.0-5.0
-carrying heavy loads or with heavy arm movements (carrying suitcases, scything, hand lawn mowing)	7.0	6.0-8.0
-transferring 35 lb sheets 2 yd at trunk level, 3 times per min	3.7	
-pushing wheelbarrow, level, with 220 lb load	5.5	5.0-6.0
-level: 2 mph	3.2	
3 mph	4.0	
4 mph	5.9	
-up: 5° grade at 3 mph	8.5	
mailman climbing stairs	12.0	
-down: 5° grade at 3 mph	3.4	

*Multiply by 4 to obtain values in Btu/min.

Source: AIHA Technical Committee on Ergonomics, 1971.

work, in RPE, is obtained using the verbal descriptions on the scale. The heart rate is 10 times the RPE.

Computation of Rest Pauses. Muller (1953) recommended rest pauses for carrying loads, carriage pulling, climbing stairs, walking, and bicycling. The net energy expenditure rate that could be performed over a day was taken as 4 kcal/min. The net energy expenditure was linearly related to the percentage of recovery time to working time. Thus for a task of duration 10 min and requiring 8 kcal/min, the rest time was shown to be 10 min.

Spitzer (1952) determined the rest pause as

$$R = \frac{M - 1}{4} \times 100$$

where R = resting time as a percentage of working time
M = net energy expenditure
= total energy cost − resting energy cost

Murrell (1964) determined the rest pause as

$$R = \frac{T \times (M - 4)}{M - 1.5}$$

where R = resting time, min
T = total working time, min
M = net energy cost, kcal/min

Mital and Shell (1985) developed a comprehensive energy model to determine rest allowances. The model is based on the worker's physical condition (age, weight, hours of sleep, fitness), the shift duration, the number of tasks performed during the shift, and the metabolic energy requirements for each task, the worker's aerobic capacity, and the energy requirement when not working. A program in BASIC to perform the computations is listed in Ayoub and Mital (1989).

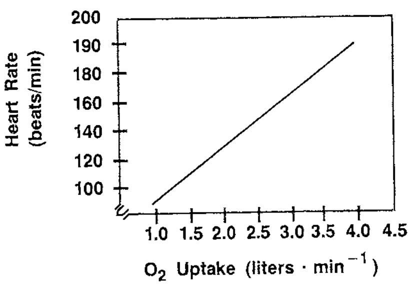


FIGURE 1.20 Relationship between heart rate and oxygen uptake. (*Astrand and Rodahl, 1986.*)

TABLE 1.11 The Borg RPE Scale

6	No exertion at all
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (heavy)
16	
17	Very Hard
18	
19	Extremely hard
20	Maximal exertion

Source: Borg, G. A. V., 1962.

WORKPLACE REDESIGN

Case Study 1: Wrist Intensive Assembly Line Operation

Problem. Over a 3-year period, reported incidences of carpal tunnel syndrome had been continually increasing. An analysis of injury data indicated that employees performing three repetitive assembly operations seemed to be particularly susceptible to these disorders and to other strains, sprains, inflammations, and muscle injuries. After consultation with the company's ergonomics task force, it was determined that a quantitative ergonomics assessment would be performed to identify potential causes of musculoskeletal injury and to develop recommendations for improving employee comfort, safety, and productivity during task performance.

Quantitative Assessment Methods. A total of 27 employees (12 female, 15 male) at the plant were assessed on-site as they performed their normal job activities. Several data types were acquired, including anthropometric characteristics of the subject population, physical requirements for task performance, job characteristics (including the number and nature of tasks performed, rotation, schedules, and shifts), work method characteristics, workstation characteristics (including dimensions and constraining factors), tool characteristics (including weight, handle size, handle shape and configuration, and center of mass), throughput and production quality requirements and environmental factors. An assessment of employee ratings of task difficulty using the Borg scale was utilized as a comparison with the quantitative findings.

Results. Owing to the nature of the tasks, the data analysis focused on the stressors place upon the shoulders, arms, and wrist during task performance. Computer analysis and digitization techniques were used to quantify the working postures, forces exertions, reach requirements, heart rate, and repetitive motions during task performance. These analyses provided an understanding of the percentage of time during which the employees maintained deviated or flexed wrist postures and to what degree. The type of grasp generally employed while gripping the tools was also determined. Figure 1.21 shows an example of the results of the postural analysis for one of the tasks evaluated.

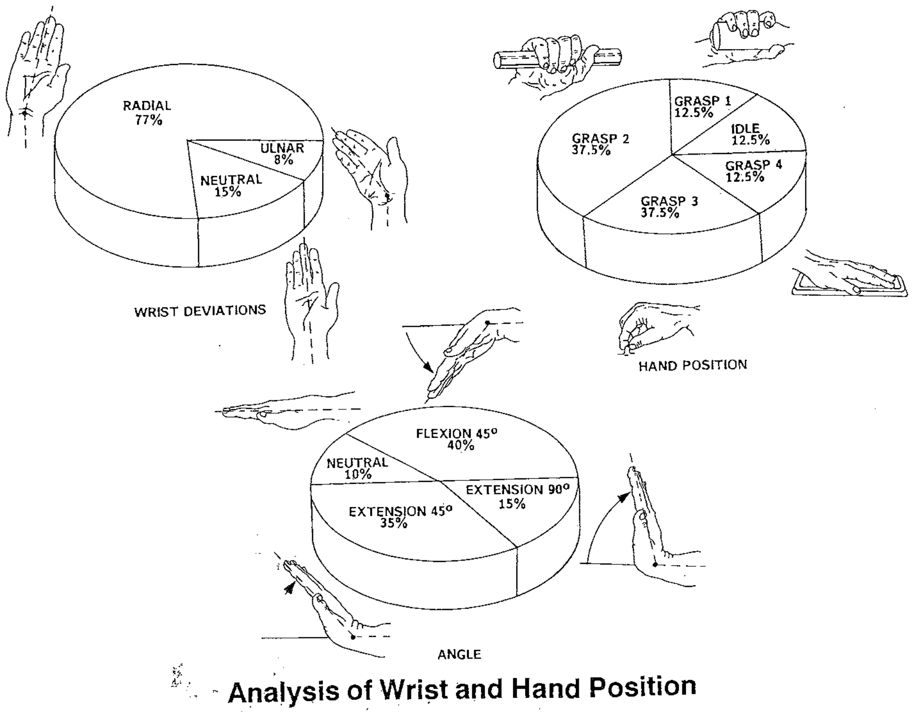


FIGURE 1.21 Postural analysis results.

An estimation of wrist injury likelihood was made by comparing the force and repetition characteristics of each task with the odds ratio suggested by Armstrong, Fine, and Silverstein (1985). According to this method, tasks which require high repetition and high force have a "high and significant" contribution to wrist injury likelihood. Tasks which require low repetition or low force have a "low and significant" contribution to wrist injury. The potential for wrist injury is generally considered "negligible" if both the force and repetition are low.

In this case, the analysis showed that the comfort and safety of the employees could be improved by modifying the design of one hand tool to improve the postural requirements to perform the task. The before and after postures required for task performance are shown in Fig. 1.22.

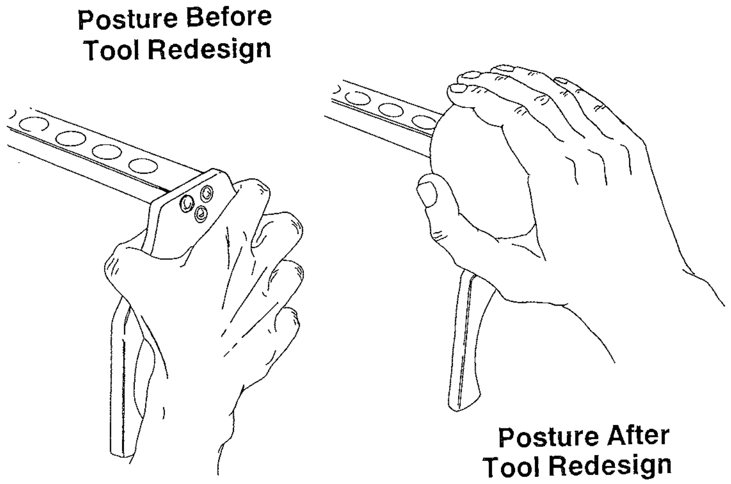


FIGURE 1.22 Postures before and after ergonomic design solution.

The procedure which was followed during the implementation of this engineering design recommendation is shown in Table 1.12. Employees who utilize the new tool receive instruction in its proper use so as to minimize musculoskeletal stress. Additional recommendations included the implementation of a job rotation schedule such that approximately four different tasks are performed by each employee during a given shift.

TABLE 1.12 Ergonomic Solution Implementation Procedure

- Development of prototype modified tool.
- Testing of prototype on small number of experience operators.
- Follow-up evaluation of employee subjective rating of comfort after using the prototype for one month.
- Refine and approve new design based on user feedback.
- Manufacture modified tool in necessary quantities.

Case Study 2: Materials Handling Operation

Problem. Increasing incidences of low back discomfort, pain, and injury in employees prompted an ergonomic assessment of the shipping dock loading job. The magnitude of the problem was further corroborated by the results of the musculoskeletal questionnaire completed during the assessment, which indicated that 80 percent of the shipping dock loaders had experienced low back discomfort during the preceding 12 months and 31 percent had been prevented from doing normal work by this discomfort.

An additional factor which had to be considered in the solution developed for reducing employee musculoskeletal stress and injury was that independent truckers were commonly used in this operation. This meant that the solution had to be mobile and located at the shipping dock as opposed to on each individual truck.

Quantitative Assessment Methods. A total of 10 male shipping dock loaders were assessed on-site as they performed their normal task of loading packages from a pallet to a trailer truck. The data acquired were similar to those described in Case 1. The most informative data for a materials handling task such as this are the videotape recordings which provide information on the angles of each body joint during task performance, the physiological data which are used to classify the difficulty of the work, and information on the physical characteristics of the workstation and the materials being transferred.

Results. The data analysis in this study focused on determining the musculoskeletal joint forces and torques on the elbow, shoulder, hip, knee, and L5/S1 spinal disk. Required strengths for the performance of the materials handling tasks were then compared with anthropometric data to determine the percentage of the normal population who would have the necessary strength to perform the tasks. The results indicated that the limiting factor for this operation was shoulder strength, with the required amount being possessed by only 38.1 percent of the U.S. male population. The spinal compressive forces upon the L5/S1 disk during this task were also found to exceed the current acceptable limit as specified by the NIOSH action limit. A summary of the data is given in Table 1.13.

TABLE 1.13 Sample Task Analysis Results

Task: Shipping Dock Loader

Working Heart Rate

Mean: 97.6 bpm
S.D.: 6.6
Range: 91-105 bpm
Classification: Heavy Work

Borg Rating of Perceived Difficulty

Mean: 13.8
S.D.: 1.2
Range: 12-15
Classification: Somewhat difficult to difficult

Maximum Compressive Force on L5/S1 disc = 1100 lb. (5057 N)*
*exceeds NIOSH Action Limit (AL) of 740 lb. (3400 N)

% of Population with Necessary Elbow Strength to Perform Task= 38%

To reduce the musculoskeletal stress resulting from manual trailer loading into independent trucks, a mobile conveyor and package placement system was recommended. This system utilizes an overhead vacuum lifting mechanism to load the required packages from the pallet to the mobile conveyor system, which is then driven into the trailer for unloading. In addition to the mechanization of this previously manual task, training in proper lifting techniques and the use of materials handling equipment was also recommended for picking of special orders from the storage rack area.

The Cost Benefits of an Ergonomics Program

The benefits of a sound biomechanically based ergonomics program are myriad. Productivity is increased, product quality is improved, musculoskeletal injuries are removed, and costs are reduced. All these results are laudable. But for the sector of the business community that is bottom-line-oriented, a question always arises as to the special manner in which costs are reduced. The cost benefits of an ergonomics program are achieved by savings in both direct and indirect costs relating to employee injuries.

The direct costs include:

- Wages paid to injured employees
- Medical expenses for treatment of injured employees
- Rehabilitation costs
- Workmen's compensation and disability insurance costs
- Lost time

The indirect costs include:

- Reductions in productivity
- Cost of replacement
- Retraining costs
- Litigation arising from employee injuries
- Supervisory costs in assisting, investigating, and reporting injuries
- Administrative costs in processing injury claims
- In-plant medical and rehabilitation costs
- Wages paid to other workers during time their work was interrupted due to injury of their coworker
- Cost of spare capacity for emergencies
- Employee turnover
- Employee absenteeism
- Reduction in employee morale

The indirect costs of injury are difficult to measure in dollars. A rule of thumb often used is that indirect costs are approximately four to eight times direct costs. Therefore, if direct costs are $1 million, the indirect costs would be a minimum of $4 million and the total cost would be $5 million.

The cost benefits of a sound, biomechanically based ergonomics program are not theoretical. They are actual if the program effort and quality are sustained. A major U.S. chemical company recently implemented such a program to detect, evaluate, and correct ergonomic problems. The focus of this program was on back injuries. The preliminary results were dramatic. The company's total recordable injuries related to on-the-job back problems were reduced by more than 50 percent. The estimated cost savings for the first year exceeded $10 million. Now this is a major cost benefit.

The cost benefits that can be achieved as the result of a sound, biomechanically based ergonomics program are substantial. The cost benefit achievable in a single year can pay for the cost of the program many times over, and the cost savings may be like an annuity, paying off in cost savings for many years to come.

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REFERENCES

AIHA Technical Committee on Ergonomics, "Ergonomics Guide to Assessment of Metabolic and Cardiac Costs of Physical Work," *AIHA Journal,* vol. 32, no. 8, pp. 560–564, 1971.

Armstrong, T. J., J. A. Foulke, B. S. Joseph, and S. A. Goldstein, "Investigation of Cumulative Trauma Disorders in a Poultry Processing Plant," *American Industrial Hygiene Association Journal,* vol. 43, pp. 103–115, 1982.

Armstrong, T. J., L. J. Fine, and B. A. Silverstein, *Occupational Risk Factors: Cumulative Trauma Disorders of the Hand and Wrist,* Final Report on Contract #200-82-2507, 1985.

Armstrong, T. J., and Y. Lifshitz, "Ergonomic Intervention Strategies for Wrist Injury Prevention," in American Conference of Governmental Industrial Hygienists, eds., *Ergonomic Interventions to Prevent Musculoskeletal Injuries in Industry,* MI: Lewis Publishers, pp. 73–75, 1987.

Asfour, S. S., Energy Cost Prediction Models for Manual Lifting and Lowering Tasks, Doctoral dissertation, Texas Tech University, 1980.

ASHRAE, Thermal Environmental Conditions for Human Occupancy (ASHRAE Standard 55-1981), American Society of Heating, Refrigeration and Air Conditioning Engineers, Atlanta, Ga., 1981. The standard for indoor thermal comfort.

Astrand, P. O., and K. Rodahl, *Textbook of Work Physiology,* McGraw-Hill, New York, 1986.

Autoweek, Should Your Car Seat Fit as Well as a Fine Suit? Mar. 12, 1990.

Ayoub, M. M., and A. Mital, *Manual Material Handling,* Taylor & Francis, London, 1989.

"Back Injuries During Lifting," Department of Labor, *Bulletin* 2144, 1982.

Barkla, D, "The Estimation of Body Measurements of the British Population in Relation to Seat Design," *Ergonomics,* vol. 21, pp. 123–132, 1961.

Bigland, B., and O. C. J. Lippold, "The Relation between Force, Velocity and Integrated Electrical Activity in Human Muscles," *Journal of Physiology,* vol. 123, pp. 214–224, 1954.

Borg, G. A. V., *Physical Performance and Perceived Exertion,* Gleerups, Lund, 1962.

Borg, G. A. V., "Physiological Bases of Perceived Exertion," *Medicine and Science in Sports and Exercise,* vol. 14, no. 5, pp. 377–381, 1982.

Bouisset, S., "EMG and Muscle Force in Normal Motor Activities," in J. E. Desmedt, ed., *New Developments in Electromyography and Clinical Neurophysiology,* vol. 1, Karger, Basel, pp. 547–583, 1973.

Brown, M. C., and J. M. Dwyer, "Repetition Strain Injury," *Proceedings of the Conference on Repetition,* New South Wales, Australia, 1984.

Bureau of National Affairs, "Job Safety: New Approaches and Heightened Expectations as 1990s Begin," *Special Report,* DER no. 12, 1990.

Burton, A. K., "Measurement of Regional Lumbar Sagittal Mobility and Posture by Means of a Flexible Curve," in N. Corlett, J. Wilson, and I. Manenica, eds., *The Ergonomics of Working Postures,* Taylor & Francis, London, 1986.

Chad, E. Y., "Experimental Methods for Biomechanical Measurements of Joint Kinematics, *CRC Handbook of Engineering in Medicine and Biology,* 385–411.

Chaffin, D., "Localized Muscle Fatigue—Definition and Measurement," *Journal of Occupational Medicine,* vol. 15.4, pp. 346–354, 1973.

Drury, C. G., "A Biomechanical Evaluation of the Repetitive Motion Injury Potential for Industrial Jobs," *Seminars in Occupational Medicine,* vol. 2, no. 1, March 1987.

Eastman Kodak Company, Human Factors Section, *Ergonomic Design for People at Work,* vol. I, Van Nostrand Reinhold, New York, 1983.

Fechner, G. T., *Sachen der Psychophysik,* Breitkopf and Hertel, Leipzig, 1860.

Fraser, T. M., *The Worker at Work,* Taylor & Francis, London, 1989.

Garg, A., A Metabolic Rate Prediction Model for Manual Material Handling Jobs, Doctoral Dissertation, University of Michigan, 1976.

Garret, J. W., "The Adult Human Hand: Some Anthropometric and Biomechanical Considerations," *Human Factors,* vol. 13, pp. 117–131, 1971.

Gilad, I., D. B. Chaffin, M. Redfern, and S. N. Byun, "System Comparison of Two Advanced Methods for Measuring Angular Displacement of Torso," in F. Aghazadeh, ed., *Trends in Ergonomics/Human Factors* V, Elsevier, New York, pp. 847–856, 1988.

Harber, P., E. Billet, M. Gutowski, K. SooHoo, M. Lew, and A. Roman, "Occupational Lowback Pain in Hospital Nurses," *Journal of Occupational Medicine,* vol. 27, pp. 518–524, 1985.

Harris, C. M., *Handbook of Noise Control,* McGraw-Hill, New York, 1979.

Hildebrandt, V., "A Review of Epidemiological Research on Risk Factors of Low Back Pain," in P. Buckle, ed., *Musculoskeletal Disorders at Work,* Taylor & Francis, London, pp. 9–16, 1987.

Hult, L., "Cervical, Dorsal and Lumbar Spinal Syndromes," *Acta Orthopedical Scandinavical,* suppl. 17.

IES (Illuminating Engineering Society of America) Industrial Lighting Committee, Proposed American National Standard Practice for Industrial Lighting, *Lighting Design and Application,* vol 13, no. 7, pp. 29–68, 1983.

IES (Illuminating Engineering Society of America) Industrial Lighting Committee, Proposed American National Standard Practice for Office Lighting, *Lighting Design and Application,* vol. 12, no. 4, pp. 27–60, 1982.

Imai, M, *Kaizen, the Key to Japan's Competitive Success,* Random House, New York, 1986.

Intaranont, K., A Study of Anaerobic Threshold for Lifting Tasks, Doctoral Dissertation, Texas Tech University, 1983.

ISO, Guide for the Evaluation of Human Exposure to Whole-Body Vibration, ISO 2631 (E), International Organization for Standardization, Geneva, 1974.

ISO, Guide for the Evaluation of Human Exposure to Whole-Body Mechanical Vibration and Shock, ISO 2631, International Organization for Standardization, Geneva, 1978.

ISO, Principles for the Measurement and the Evaluation of Human Exposure to Vibration Transmitted to the Hand, DIS 5349.1, International Organization for Standardization, Geneva, 1979.

ISO, Guidelines for the Measurement and the Assessment of Human Exposure to Hand-Transmitted Vibration, DIS 5349.2, International Organization for Standardization, Geneva, 1984.

ISO, Evaluation of Human Exposure to Whole-Body Vibration, Part I: General Requirements, ISO 2631/1-1985, International Organization for Standardization, Geneva, 1985.

ISO, Hand-Held Power Tools—Measurement of Vibrations at the Handle, Part 1: General, ISO 8662/1, International Organization for Standardization, Geneva, 1988.

Jensen, R. C., "Events That Trigger Disabling Back Pains among Nurses," *Proceedings of the 29th Annual Meeting of the Human Factors Society,* pp. 799–801, 1985.

Jensen, R. C., "Work Related Back Injuries among Nursing Personnel in New York," *Proceedings of the 29th Annual Meeting of the Human Factors Society,* pp. 244–248, 1986.

Johnston, R. C., and G. L. Smidt, "Measurement of Hip-Joint Motion during Walking," *The Journal of Bone and Joint Surgery,* vol. 51-A, no. 6, pp. 1083–1094, 1969.

Jones, D. M., and A. J. Chapman, *Noise and Society,* Wiley, Great Britain, 1984.

Kaufman, J. E., and H. Haynes, *IES Lighting Handbook,* reference volume, Illuminating Engineering Society of America, New York, 1981a.

Kaufman, J. E., and H. Haynes, *IES Lighting Handbook,* applications volume, Illuminating Engineering Society of America, New York, 1981b.

Kettelkamp, D. B., R. J. Johnson, G. L. Smidt, E. Y. S. Chao, and M. Walker, "An Electrogoniometer Study of Knee Motion in Normal Gait," *The Journal of Bone and Joint Surgery,* vol. 52-A, no. 4, pp. 775–790, 1970.

Khalil, T. M., S. S. Asfour, and E. A. Moty, "Case Studies in Low Back Pain," *Proceedings of the 28th Annual Meeting of the Human Factors Society,* pp. 465–470, 1984.

Kivi, P., "Rheumatic Disorders of the Upper Limbs Associated with Repetitive Occupational Tasks in Finland in 1975–1979," *Scandinavian Journal of Work, Environment, and Health,* 5, Supplement 3, 1984.

Klein, B. P., M. A. Roger, R. C. Jensen, and L. M. Sanderson, "Assessment of Workers' Compensation Claims for Back Sprain/Strains," *Journal of Occupational Medicine,* vol. 27, pp. 443–448, 1984.

Kroemer, K. H. E., H. J. Kroemer, and H. E. Kroemer-Elbert, *Engineering Physiology: Physiologic Bases of Human Factors Ergonomics,* vol. 4 in G. Salvendy, ed., *Advances in Human Factors/Ergonomics,* Elsevier, Amsterdam, 1986.

Lawther, A., and M. J. Griffin, "Measurement of Ship Motion," in D. J. Oborne and J. A. Lewis, eds., *Human Factors in Transport Research,* vol. 2, *User Factors: Comfort, The Environment and Behavior,* Academic Press, London, pp. 131–139, 1980.

Mandell, P., M. H. Lipton, J. Bernstein, G. J. Kucera, and J. A. Kampner, *Low Back Pain,* Slack International, New Jersey, 1989.

Mital, A., and R. L. Shell, "A Comprehensive Metabolic Energy Model for Determining Rest Allowance for Physical Tasks," *Journal of Methods Time Measurement*, vol. 9, pp. 2–8, 1985.

Morgan, R. P., and A. Bhattacharya, "Force Platform Technique for the Quantification of Postural Change Induced by Alcohol Indigestion," in A. Mital, ed., *Trends in Ergonomics/Human Factors* I, Elsevier, New York, 1984.

Muller, E. A., "Physiological Basis of Rest Pauses in Heavy Work," *Quarterly Journal of Experimental Physiology*, vol. 38, pp. 25–215, 1953.

NIOSH, *A Work Practices Guide for Manual Lifting*, Technical Report No. 81-122, U.S. Department of Health and Human Services, National Institute for Occupational Safety and Health, Cincinnati, Ohio, 1981.

NIOSH, Criteria for Recommended Standard–Occupational Exposure to Noise, U.S. Department of Health, Education and Welfare, National Institute for Occupational Safety and Health, Cincinnati, 1972.

Nordin, M., G. Hultman, R. Philipsson, A. Ortelius, and G. B. J. Andersson, "Dynamic Measurements of Trunk Movements during Work Tasks," in N. Corlett, J. Wilson, and I. Manenica, eds., *The Ergonomics of Working Postures*, Taylor & Francis, London, 1986.

Nordin, M., Methods for Studying Workload, with Special Reference to the Lumbar Spine, thesis, Goteborg, 1982.

O'Brien, C., and M. G. A. Paradise, "The Development of a Portable Non-invasive System for Analyzing Human Movement," *Proceedings of the Sixth Congress of the International Ergonomics Association*, Maryland, pp 390–392, July 1976.

Petrofsky, J. S., "Computer Analysis of the Surface EMG during Isometric Exercise," *Computers in Biology and Medicine*, vol. 45, pp. 83–95, 1979.

Pheasant, S., *Bodyspace: Anthropometry, Ergonomics, and Design*, Taylor & Francis, London, 1986.

Pinkham, J., "CTS Impacts Thousands and Costs are Skyrocketing," *Occupational Health and Safety*, August, 1988.

Rohmert, W., *Die Beziehung zwischen Kraft und Ausdauer bei Statischer Muskelarbeit*, Schrifteneihe Arbeitsmedizin Sozialmedizin Arbeitshygiene, Band 22, p. 118. A. W. Gentner Verlag, Stuttgart, 1968.

Schoenmarklin, R. W., and W. S. Marras, "Validation of a Hand/Wrist Electromechanical Goniometer," *Proceedings of the Human Factors Society 33rd Annual Meeting*, pp. 718–722, 1989.

Sheng, W., and C. M. Gross, Carpal Tunnel Syndrome: A Review of the Literature, 1988.

Silverstein, B., L. Fine, T. Armstrong, B. Joseph, B. Buchholz, and M. Robertson, "Cumulative Trauma Disorders of the Hand and Wrist in Industry," in N. Corlett, J. Wilson, and I. Manenica, eds., *The Ergonomics of Working Postures*, Taylor & Francis, London, 1986.

Snook, S. H., "The Design of Manual Handling Tasks," *Ergonomics*, vol. 21, pp. 963–985, 1978.

Society of Automotive Engineers, "Measurement of Whole Body Vibration of the Seated Operator of Agricultural Equipment (the Society of Automotive Engineers recommended practice)," *Society of Automotive Engineers SAE J1013 Handbook*, Part II, pp. 1404–1407, Society of Automotive Engineers, Detroit, Mich., 1974.

Spitzer, H., *Physiologische Grundlagen für den Erholungszuschlag bei Schwerarbeit*, REFA-Nachrichten, Darmstadt, 1952.

Svensson, H. O., and G. B. H. Andersson, "Low-Back Pain in 40–47 Year Old Men: Work History and Work Environment Factors, *Spine*, vol. 3, pp. 272–276, 1983.

Weber, J., A. van der Star, and C. J. Snijders, "Development and Evaluation of a New Instrument for the Measurement of Work Postures; in Particular the Inclination of the Head and the Spinal Column," in N. Corlett, J. Wilson, and I. Manenica, eds., *The Ergonomics of Working Postures*, Taylor & Francis, London, 1986.

Weber, E. H., De pulse, resorptione, auditu et tacticu, Kochler, Leipzig, 1834.

Whitham, E. M., and M. J. Griffin, "Measuring Vibration on Soft Seats," Society of Automotive Engineering Paper no. SAE 770253, International Automotive Engineering Congress and Exposition, Detroit, 1977.

Wilson, J. R., and N. C. Corlett, eds., *Evaluation of Human Work, a Practical Ergonomics Methodology*, Taylor & Francis, London, 1990.

Winter, D. A., G. Rau, and R. Kadefors, "Units, Terms and Standards in the Reporting of Electromyographical Research," in 4th Congress of the International Society of Electromyographical Kinesiology, Boston, 1979.