## CHAPTER 32

# ERGONOMIC ASPECTS OF BIOMECHANICS

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## INTRODUCTION

Biomechanics is the discipline dedicated to the study of the living body as a structure which can function properly only within the confines of both the laws of Newtonian Mechanics as well as the biological laws of life. Bomechanics is by no means a new pursuit. The mechanics of locomotion of many animals and birds were researched in depth as early as during the 17th century by Borelli.[1] In the course of the next century, Bernouilli[2] published a treatise on the "physiomechanics" of muscle movement. A contemporary of Bernouilli, Bernardino Ramazzini,[3] the father of occupational medicine, discussed in his book "De Morbus Artificum" (about the diseases of workers) in remarkable detail the ill effects of poor posture and poorly designed tools on man. In the preface to the 1700 edition of his text he writes ". . . Manifold is the harvest of diseases reaped by certain workers from the crafts and trades that they pursue; all the profit they get is injury to their health. That stems mostly I think, from two causes. The first and most potent is the harmful character of the materials that they handle, noxious vapors and very fine particles, inimical to human beings, inducing specific diseases. As the second cause I assign certain violent and irregular motions and unnatural postures of the body, by reason of which the natural structure of the living machine is so impaired that serious diseases gradually develop therefrom . . ." For nearly two centuries industrial hygiene and related disciplines limited their scope of interest to the first set of occupational disease vectors as discussed by Ramazzini. They were easily identified and in many instances amenable to control by procedures already then available to industrial hygienists. Simultaneously, however, positive and aggressive steps were taken to develop energetically other fields of scientific endeavor basic to the maintenance of occupational safety and health. An unbroken chain of endeavors by physicists and physiologists since Lavoisier[4] provided the basic data necessary to develop metabolic studies and ergonometry into reliable procedures, applicable to the measurement of effort expended by man at work.

The publications of Benedict and Cathcart[5] in 1913 and of Amar[6] in 1917 are among the first acquainting practitioners in industry with the application of ergometry to work measurement. Towards the end of World War I, the general interest in work physiology widened and deepened in the United States, Britain, France and Germany. Dire manpower needs forced the women of these countries to forego their rather sheltered victorian style of life and to accept employment in ammunition factories and other occupations that up to then had been considered distinctly unfeminine. They performed jobs strange to them in an environment they had never known before; emotional and physiological considerations caused problems in efficiency, hygiene and safety, which in turn stimulated research, especially as related to the effects of heat[7] as well as light on both output and physical comfort of workers.

By the end of the hostilities, both work physiology as well as industrial psychology had become firmly established albeit quite separate disciplines.

The events of World War II and their social and economic after-effects gave impetus to the consolidation of a number of narrow specialties into a broad, unified and generally accepted separate discipline dedicated to the academic as well as the applied study of man at work: Ergonomics. Also, the Ergonomics Research Society was founded in England. Its membership developed rapidly on a world-wide basis. However, in the immediate post-war years the practice of ergonomics was of prime importance to European countries where, as a matter of economic survival, consumer goods industries had to be rebuilt fast. Their working population was still untrained in the use of modern technology that had meanwhile developed in the United States. Workers were also generally undernourished and worn out from years of struggle and many of them were physically handicapped. Thus, ergonomics was first applied to overcome the serious and general problems involved in fitting jobs to the physical and behavioral operating characteristics of individual workers. This involved a broader study of the relationship between man and his environment, the design of equipment and particularly the application of anatomical, physiological and psychological knowledge to the solution of problems arising from equipment and environment. This new systems approach to problems common to occupational safety and health as well as industrial efficiency required new and deeper understanding of the mechanics of the living body at work.[8, 9]

Occupational Biomechanics was added as a new tributary to the pool of general knowledge essentrial to the understanding of the complex mechanisms of interaction between the worker and the industrial environment.

The industrial environment as opposed to work environment (including, e.g., farming) is unique in several aspects. Firstly, it is entirely man-conceived, man-made and purposefully designed with one objective in mind: to maximize economic efficiency of human performance. Physiological performance and comfort of the working population, at least until recently, were only considered inasmuch as they were conducive to higher levels of productivity. Thus, by implication, those who are responsible for the maintenance of occupational safety and health have to overcome many biomechanical, physiological and behavioral hazard vectors likely to be overlooked in the design of the industrial environment.

It is the purpose of this chapter to describe occupational biomechanics as a subdiscipline of ergonomics which can be applied by professionals active in the health as well as technological sciences for the purpose of achieving maximal physiological and emotional well-being of the working population, while at the same time enhancing the economic efficiency of industrial undertakings as a whole. In our modern industrial environment efficiency is a by-product of comfort. The enterprise that manufactures no sore backs, shoulders, wrists or behinds is at a competitive advantage over one with suffering workers.[10]

The information provided in this chapter will be adequate for a general biomechanical evaluation of workplaces, machinery, handtools, chairs, lifting tasks and industrial work situations in general.

The Ergonomics Research Society: The Origin of Ergonomics. Loughborough, England, Echo Press, 1964.

Figure 32-1. Illustration symbolizes the concept of modern ergonomics (biomechanics). Worker is surrounded by external physiological and mechanical environments which have to be matched to his internal physiological and biomechanical environments.

## THE ANATOMY OF FUNCTION

Anatomy is concerned with the description and classification of biological structures. Systematic anatomy describes the physical arrangement of the various physiological systems (e.g., anatomy of the cardiovascular system); topographic anatomy describes the arrangement of the various organs, muscular, bony and neural features with respect to each other (e.g., the anatomy of the abdominal cavity); and functional anatomy focuses upon the structural basis of biological function (e.g., description of the heart valves and ancillary operating structures, description of the anatomy of joints). As distinct and different from the aforementioned, the anatomy of function is concerned with the analysis of the operating characteristics of anatomical structures and systems when these interact with physical features of the environment such as is the case in the performance of an industrial task. Modern occupational biomechanics considers the worker as the monitoring link of a man-equipment-task system. In such a situation, man is enveloped by the "external mechanical environment" (Figure 32-1) which is an array of machinery, levers, pushbuttons, and such other equipment as may pertain to the immediate working environment of the individual. Located inside of the human skin is the "internal biomechanical environment" which may be presumed, at the risk of oversimplification, to be identical with the neuro-musculo-skeletal system. If the "motions and reactions inventory" demanded by the external environment is not compatible with the one available from the internal biomechanical environment, then discomfort, trauma and inefficiency may ensue.

The anatomy of function is the structural basis of human performance and thus provides much of the rationale by which the output measurements derived from work physiology and engineering psychology can be explained.

### Lever Systems Within the Human Body

The musculo-skeletal system is an array of bony levers connected by joints and actuated by muscles. With few exceptions, lever classifications and taxonomy in both anatomy and applied mechanics are identical. Each class of anatomical lever is specifically suited to perform certain types of movement and postural adjustments efficiently and without undue risk of accidents while it may be less suited to perform other equally specific maneuvers. Therefore a good working knowledge of location, function and limitation of anatomical levers involved in specific occupational maneuvers is a prerequisite essential for the ergonomic analysis and evaluation of most man-task systems.

*First Class Levers* have force and load located on either side of the fulcrum acting in the same direction but opposed to any force supporting the fulcrum (Figure 32-2). This is exemplified by the arrangement of those musculo-skeletal structures as are involved in head movement in looking up and down. Then the atlanto-occipital joint acts as the fulcrum of a first class lever because the muscles of the neck provide the force necessary to extend the head. This is counteracted by gravity acting on the center of mass of the head which is located on the other side of the joint, and hence constitutes an opposing flexing weight. First class levers are often found where fine positional adjustments are required. In standing or the static holding of bulky loads, head movement in the midsagittal plane produces the fine adjustment of the position in the center of mass of the whole body necessary to maintain upright posture (Figure 32-3). Individuals suffering from impaired head movement (e.g., arthritis of the neck), should not be exposed to tasks where inability to maintain postural equilibrium constitutes a substantial hazard. Likewise, workplaces where free and unrestricted head movement is difficult should be provided with either chairs or other means of postural stabilization.

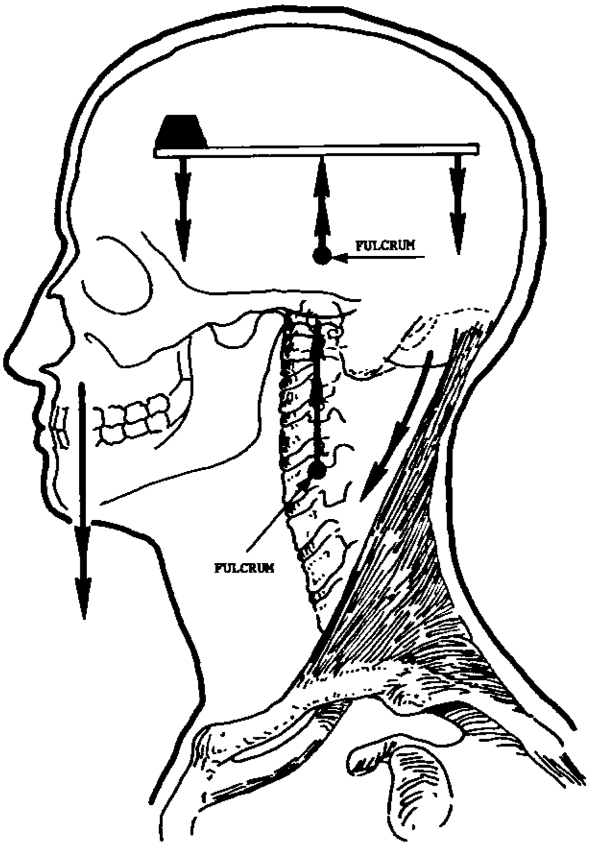
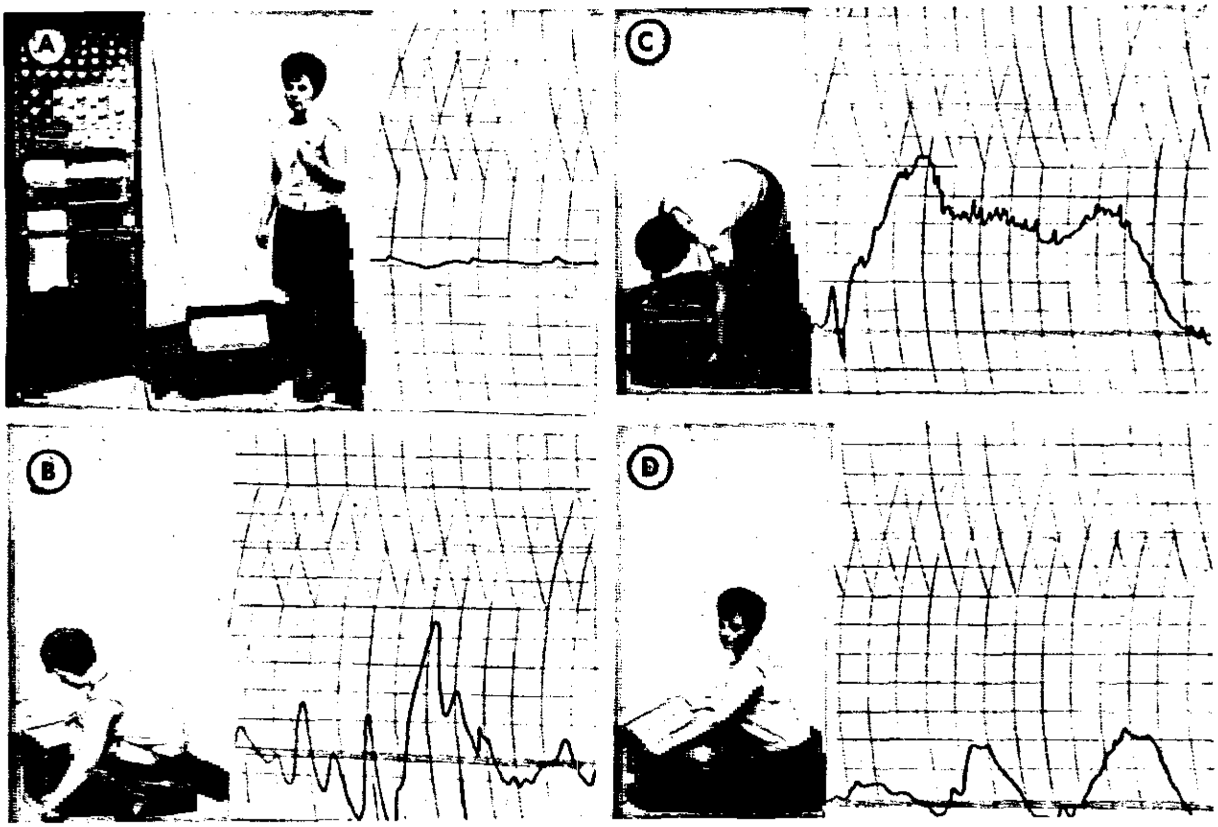


Figure 32-2. The action of the muscles of the neck against the weight of the head is an example of a first class lever formed by anatomical structures. The atlanto-occipital joint acts as a fulcrum.

*Second Class Levers* have the fulcrum located at one end, the force acts upon the other end but in the same direction as the supporting force of the fulcrum. The weight acts upon any point between fulcrum and force in a direction opposed to both of them. Second Class Levers are optimally associated with ballistic movements requiring some force and resulting in modifications of stance, posture or limb configurations. The muscles in-



Tichauer, E. R.: Ergonomics: The state of the art. Amer. Ind. Hyg. Assoc. J. 28:105-16, 1967.

Figure 32-3. Myograms of the Sacrospinalis Muscle during a Lifting Task. It can be seen how activity in this muscle varies according to posture. (A) upright posture showing electrosilence in muscle. (B) failure to hold head upright in straight-back, bent-knee lift results in strong postural reactions recorded by the myogram. (C) straight-knee, bent-back lift, showing high strain in sacro-spinalis muscle. (D) straight-back, bent-knee, head-up lift, showing less stress in sacro-spinalis muscle.[8]

serted into the heel by way of the achilles tendon (i.e., force), the weight of the body transmitted through the ankle joint, and the base of the big toe (i.e., fulcrum) are a good example of a second class lever system used in locomotion (Figure 32-4).

*Third Class Levers* have the fulcrum at one end, the weight acts upon the other end, in the same direction as the supporting force of the fulcrum. The "force" itself acts upon any point between weight and fulcrum but in a direction opposed to both of them. Tasks which require the application of strong but voluntarily graded force are often best performed by this type of anatomical lever system. Holding a load with forearm and hand when the brachialis muscle acts upon the ulna with the elbow joint constituting the pivot is a typical example (Figure 32-5).

Torsional Levers are a specialized case of the Third Class Lever (Figure 32-6). Here the axis of rotation of a limb or long bone constitutes the fulcrum. The force-generating muscle of the system is inserted into a bony prominence and produces rotation of the limb whenever the muscle contracts. The "weight" is constituted by the inertia of the limb plus any external torque opposing rotation. An example is the supination of the flexed forearm. Here the fulcrum is the longitudinal axis of the radius, the force is exerted by the biceps muscle inserted into the bicipital tuberosity of the radius while the opposing load may be the inertia of forearm and hand plus the resistance of, for example, a screw driven home. Tasks to be performed with strength and precision and at variable rates of speed are best assigned to torsional lever systems.

An inexpensive anatomical atlas for artists constitutes a useful aid in task analysis and design whenever an evaluation of the effectiveness of the anatomical lever systems employed is under consideration.

### Range and Strength of Limb Movement

The absolute range of limb movement is limited by the mechanical configuration of the joints. For example, due to interference of the olecranon, it is impossible to extend the angle between forearm and upper arm beyond 180°. Likewise, the location of the point of insertion of the brachialis tendon into the ulna makes it impossible to flex the joint to an angle of less than 15°. This re-

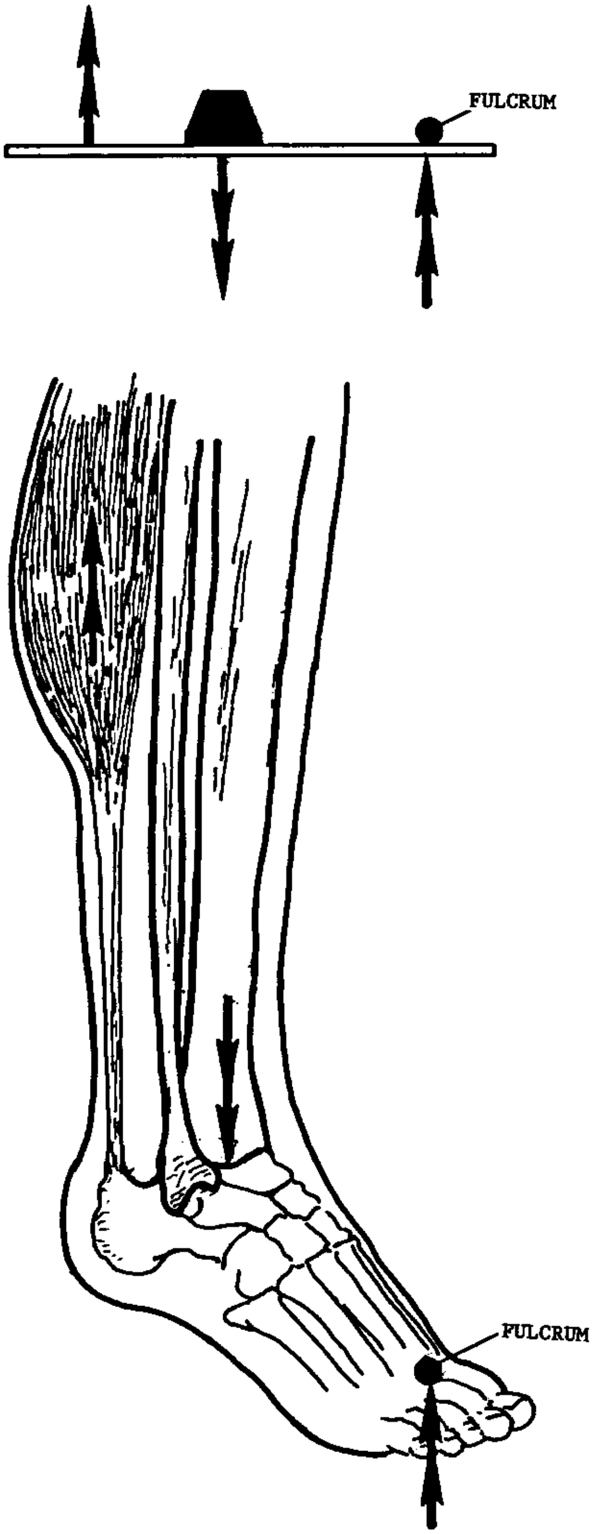


Figure 32-4. The Ankle Joint, as an Example of an Anatomical Second Class Lever System. The fulcrum is located at the base of the big toe.

sults in a total range of 165°. In occupational biomechanics, however, not the total but only the effective range of movement is of significance (Figure 32-7). Muscles behave like extension springs. They can exert no force when fully contracted and exert maximal force when fully extended. Between these two states, potential force varies linearly as a degree of extension. Further complexities are introduced into the system because the "mechanical advantage" to which it can be applied varies with the degree of joint flexion. In physics "mechanical advantage" is defined as ". . . ratio of the weight of the actual load raised to the force input required to perform," [paraphrased from (11)]. Therefore, the mechanical advantage with which the potential force of the muscle can be applied does not vary linearly, but changes in proportion to the sine of the angle between the bony elements of the lever system. This results in a narrow angular range within which limb movement is strong as well as precise and outside of which not only effectiveness of motion decreases, but individual differences increase to such an extent that performance becomes virtually unpredictable. There are many compilations in tabular form available, useful in estimating range and strength of limb movement for a given work situation.[12, 13, 14] Partial recapitulation of the comprehensive data presented in the references mentioned would not only be redundant but could also tempt readers to rely on fragmentary and insufficient information as a basis for decision making. Most anthropometric reference works, however, were developed as aids in the design of specialized man-task systems such as the operation of motor vehicles,[15] or military aircraft, and therefore some information might not be applicable without a degree of modification to generalized work situations. Also many references state range of joint movement over the full angle and strength of movement in terms of maximum and therefore these data, with the help of an anatomical atlas or, better, an articulated plastic skeleton, should always be reduced to the "effective range" for a specific task or for a specialized working population (Figure 32-8).

### Kinetic Elements

The functional aggregate of all anatomical structures involved in producing a simple movement of a joint about one of its axes is called a "kinetic element" (Figure 32-9).

The basic structure of each kinetic element is a lever system consisting of at least two bones connected by a joint. The levers are moved by the contraction of muscles inserted into the bones. These muscles are arranged to oppose each other. The action muscle is termed "protagonist;" the opposer, "antagonist." Contraction occurs in response to stimuli from the specific nerve supplying each muscle. The oxygen required for the energy release needed to bring about muscular contraction is provided by arterial branches supplying protagonists as well as antagonists with blood. The waste products of the physiological combustion process incidental to energy release are carried away by venous or other drainage mechanisms. Thus, each kinetic element is made up of the following constituents:

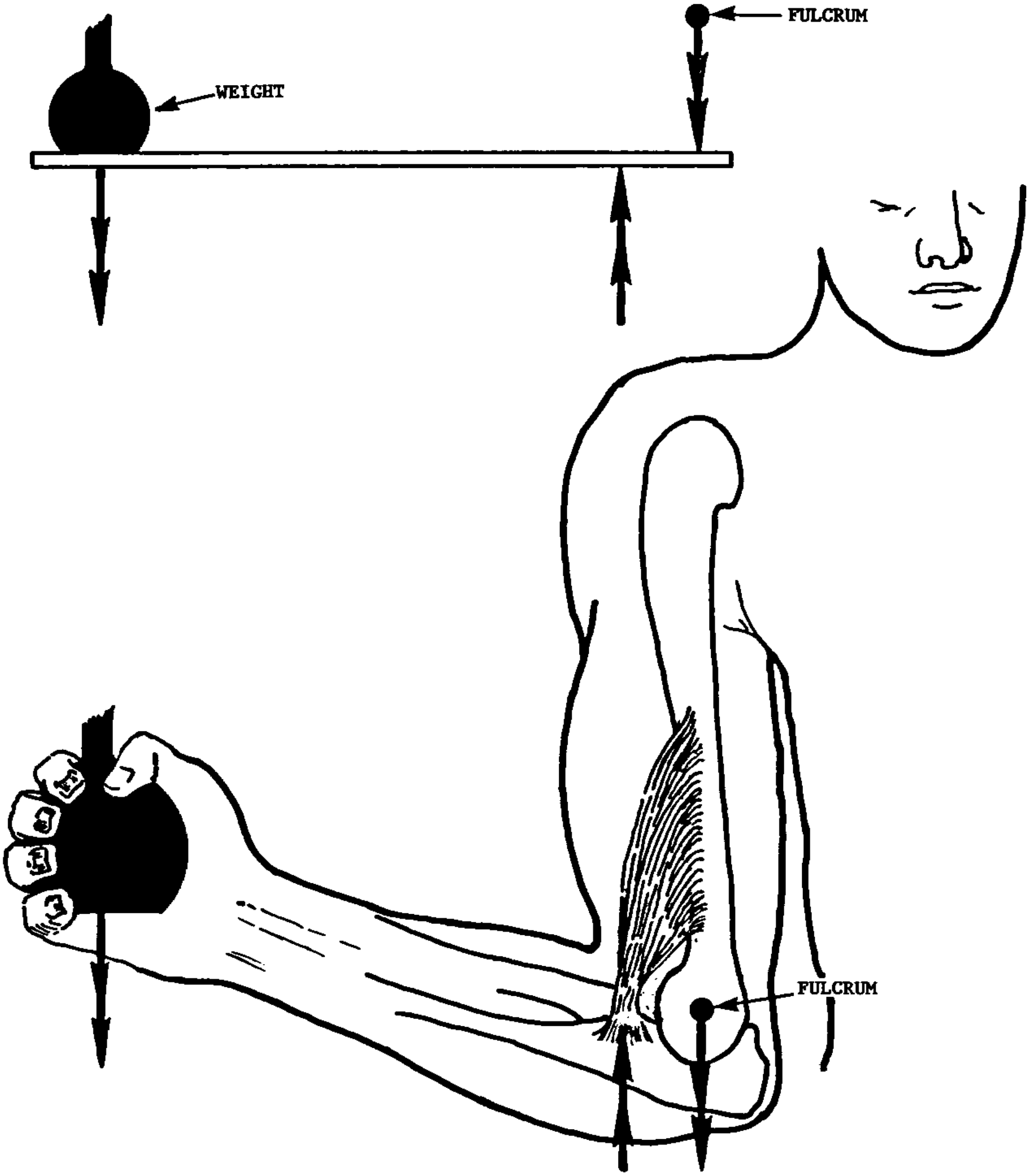
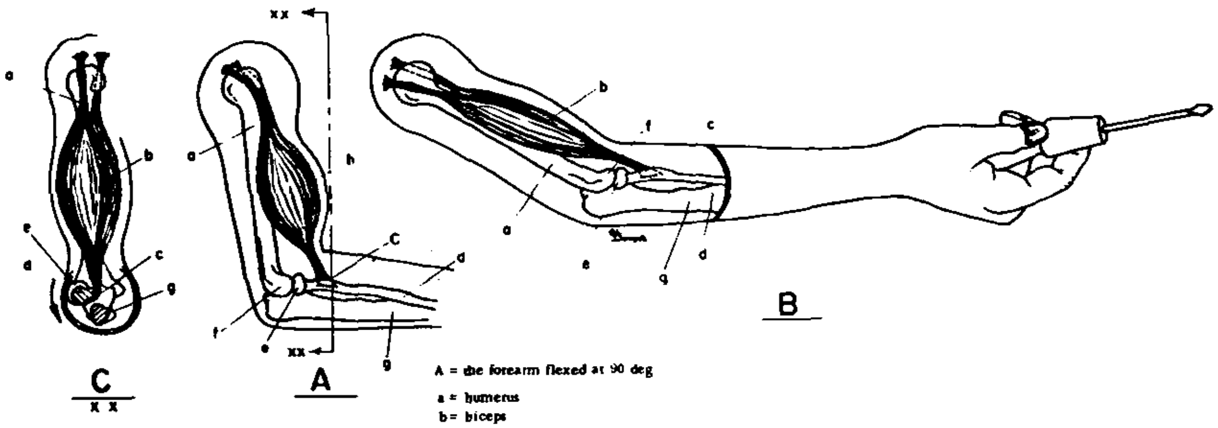


Figure 32-5. An anatomical third class lever is formed between ulna and humerus. The brachialis muscle provides the activating force, the fulcrum is formed by the center of the trochlea of the humerus.



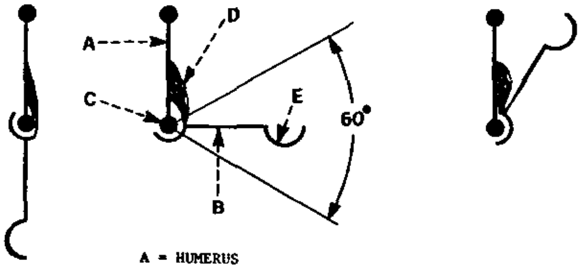
A = the forearm flexed at 90 deg

a = humerus
b = biceps
c = attachment of biceps
d = radius
e = head of radius
f = capitulum of humerus
g = ulna
B = The angle of the forearm extended when the efficiency of the biceps as an outward rotator is reduced. Here the muscles will pull the radius strongly against the humerus causing friction and heat in the joint

C = Cross section X-X through A showing why the biceps is an outward rotator of the forearm

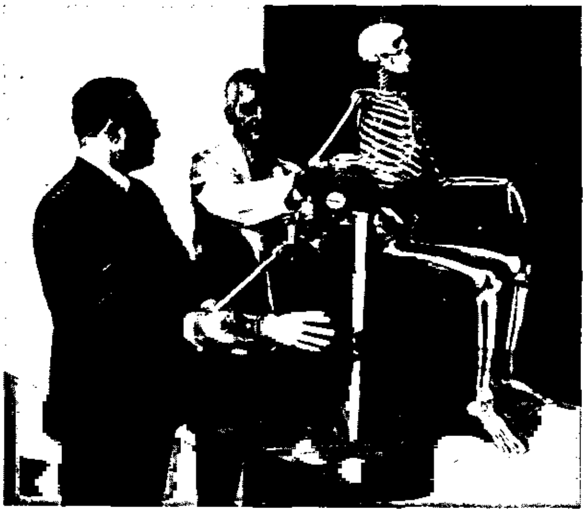
Tichauer, E. R.: The Biomechanics of the Arm-Back Aggregate under Industrial Working Conditions. New York, American Society of Mechanical Engineers, 1965.

**Figure 32-6. A Torsional Lever System Exemplified by the Kinetic Element Made Up of Humerus, Radius and Biceps.**



A = HUMERUS
B = ULNA
C = HUMERO-ULNAR JOINT
D = BRACHIALIS MUSCLE
E = HAND

**Figure 32-7. The kinetic element formed between humerus, ulna and brachialis muscle can operate at best mechanical advantage only within a relatively narrow angle of forearm flexion.**



Western Electric News Features, New York, 1965.

**Figure 32-8. The Use of a Plastic Skeleton for the Objective Analysis of Biomechanical Advantage of a Specific Working Posture. Possible stresses in the shoulder joint are measured with the mechanical analog along side.**

1. bony;
2. articular;
3. muscular;
4. nervous; and
5. vascular.

Only the simplest and most basic of all motions such as, for example, reflex reactions, involve only one kinetic element. In the industrial environment, manipulative as well as locomotive maneuvers are normally performed by a "kinetic chain."

**Kinetic Chains**

A kinetic chain consists of a number of serially interacting kinetic elements reacting to inputs and

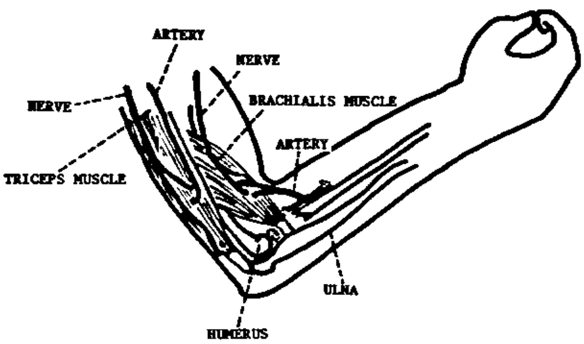
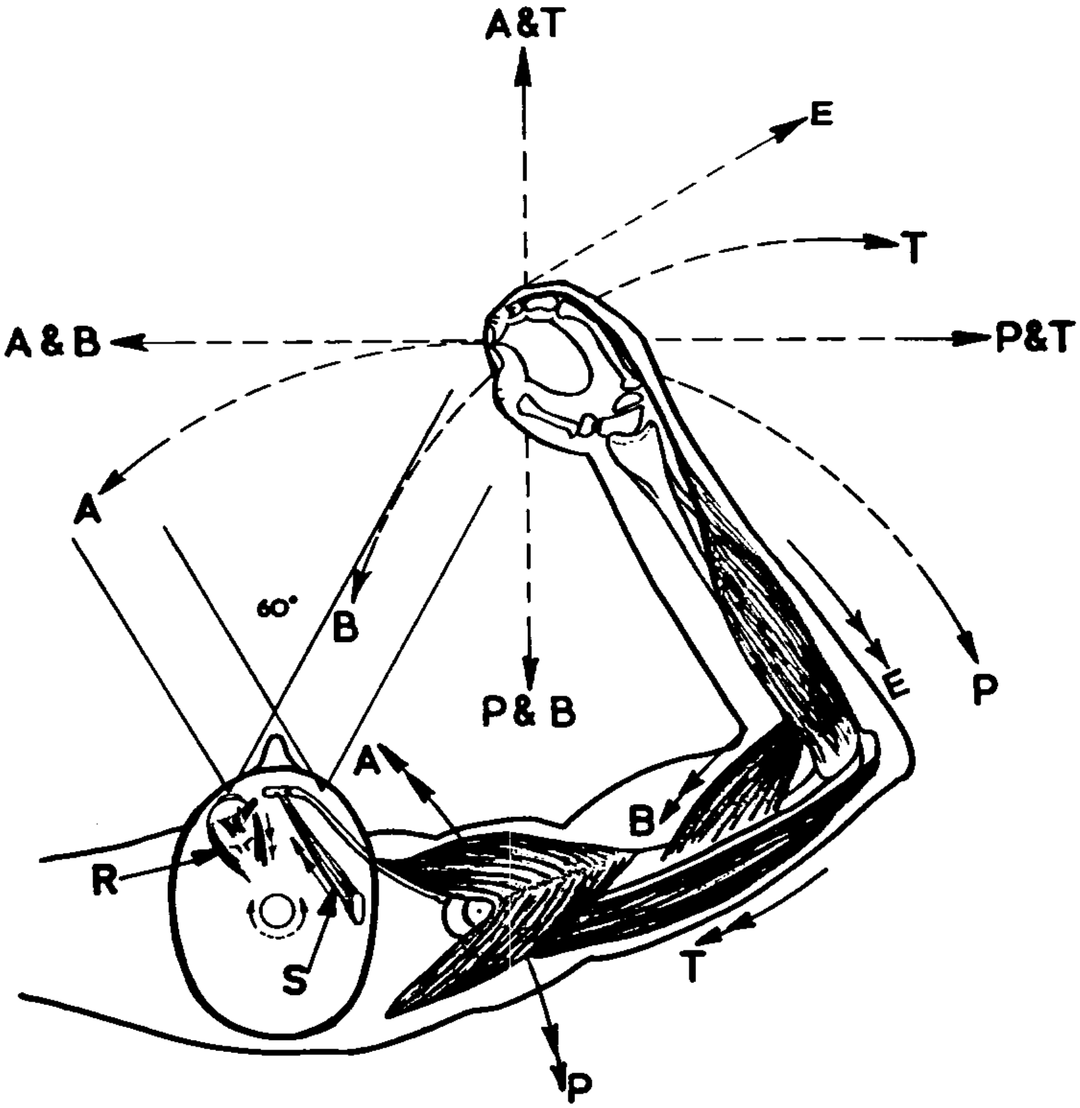


Figure 32-9. The Kinetic Element of Forearm Flexion and Extension.

feedbacks perceived from within and without the body by sensory organs connected with the kinetic element in such a manner as to form a cybernetic, or self-regulating system. The first step in the biomechanical evaluation of a workplace is normally the identification of that kinetic chain which links sensory inputs or feedbacks from the workplace with the muscular output required to perform a specific task.[16] To enumerate all anatomical structures of a kinetic chain is not only cumbersome, but often unnecessary. Therefore, in industrial practice the description of a kinetic chain includes only major sensory organs and key kinetic elements.

The kinetic chain of "eye-hand coordination" is perhaps the most frequently used one in most industries (Figure 32-10). Here the main sensory input is perceived by the eyes. These track the visual target when moved by the small muscles



Tichauer, E. R., Gage, H., Harrison, L. B.: The Use of Biomechanical Profiles in Objective Work Measurement. J. Ind. Eng. IV:20-27, 1972.

Figure 32-10. The Kinetic Chain of Eye-Hand Coordination.

(Figure 32-10/R) which rotate the eyeball. However, binocular vision and thus, depth perception, exists only within the binocular visual cone of 60°. To bring binocular vision to bear upon an object positioned outside of this cone, it becomes necessary to rotate the head and thus the next kinetic element in the chain is formed by the sternomastoid muscle (Figure 32-10/S) and its connection with the skull and the breastbone. Subsequent to visual evaluation of the work situation, a forward movement of the arm about the shoulder is produced by the anterior belly of the deltoid muscle (Figure 32-10/A) which is antagonized and controlled by activity of the posterior belly (Figure 32-10/P) of the same muscle. To reach out, the triceps inserting into the ulna functions as protagonist and this action is opposed and controlled by the brachialis, (Figure 32-10/T and 32-10/B) which, in turn, originates from the humerus and inserts into the ulna. Fine positioning of the wrist is governed by, among others, a complex group of extensor muscles (Figure 32-10/E), originating from the elbow region and inserted into the phalanges of the fingers. Identification of such a kinetic chain makes it possible to compare, without physical experimentation, the anatomical complexity of motions performed under visual control in various directions, and to eliminate those which are likely to be the most fatiguing motions. In Figure 32-10 motion pathway B would be very easy to perform, requiring only the use of the brachialis muscle while motion pathways A & B and P & T would very likely lead to early fatigue as such action demands the use of every element, sensory as well as motor, in the kinetic chain.

Likewise, correct identification of the kinetic chain permits the spotting, and often the elimination, of potential anatomical failure points in a man-task system.

### Anatomical Failure Points in Man-Task Systems

Whenever, in a man-task system, an element in a kinetic chain is structurally overstressed so that the maintenance of economically acceptable production rates or product quality becomes impossible without impairing the worker's physiological or emotional well-being, then the kinetic element under consideration becomes an actual or potential anatomical failure point.

Quite frequently, workplace design in accordance with established industrial engineering principles is conducive to the generation of such failure points. The principles of work simplification and other work measurement and design techniques did not change at the same pace as the development of modern industrial technologies. Many reputable industrial engineering texts[17] still recognize only five different classifications of motion:

1. finger;
2. fingers and wrists;
3. fingers, wrists and forearm;
4. fingers, wrists, forearm and upper arm; and
5. all of the above (1-4) plus a body motion or a change of posture.

These texts or common usage[17] further stipulate "... required motions should be performed within the lowest classification possible . . . any motion beyond the maximum for 4th class should be avoided if at all possible. The shorter the motion, the less time and effort it will take to perform it . . ." This approach has simply become untenable in this age of pushbutton-operated machinery and miniaturization.

Even the simplest of man-task systems, unless screened while still in the planning stage, for potential anatomical failure points, can adversely affect health as well as performance of large numbers of workers.[18] For example, the ergonomic efficiency and safety of a screwdriving task depends primarily on the magnitude of the included angle between forearm and upper arm in habitual working posture. If workers are permitted to position themselves only a few inches too far away from the workplace, then the incidence of sore elbows at the workplace, be they classified as epicondylitis, bursitis, or by any other name, will increase dramatically (Figure 32-11). This can be explained and avoided by biomechanical analysis of the relevant kinetic element. The biceps is not only a flexor of the forearm but also, due to the mode of its attachment to the radius, the most powerful lateral rotator of the wrist (Figure 32-11/c). Whenever working posture is such that the angle between forearm and upper arm approximates 90° (Figure 32-11), then this muscle operates at mechanical advantage. However, if a posture is assumed which increases this angle (Figure 32-11), then the biceps also jams the head of the radius against the capitulum of the humerus generating friction, heat, and ultimately conditions commonly classified as epicondylitis. This example is typical of the numerous work situations where effective occupational hazard control can be exercised through identification of anatomical failure points in a man-task system.

A kinetic element is a potential failure point when:

a. the degrees of freedom of movement required exceed those available from the lever system employed;
b. the lever system has to perform for extended periods of time at mechanical disadvantage or under conditions of high stress concentration at the joint surfaces;
c. the muscles employed are too small to maintain performance for prolonged intervals of time;
d. the blood supply to the muscles is impaired; and
e. sensory feedback is defective or equivocal.

## ANTHROPOMETRY

Industrial Anthropometry is the discipline concerned with the body measurements of man as they relate to the maintenance of occupational efficiency, safety and health. A number of excellent reference works containing complete sets of numerical data are available in this field,[19, 20] so that partial recapitulation of numerical material here would not only be redundant but, due to the necessary oversimplification in presentation, dangerously misleading.

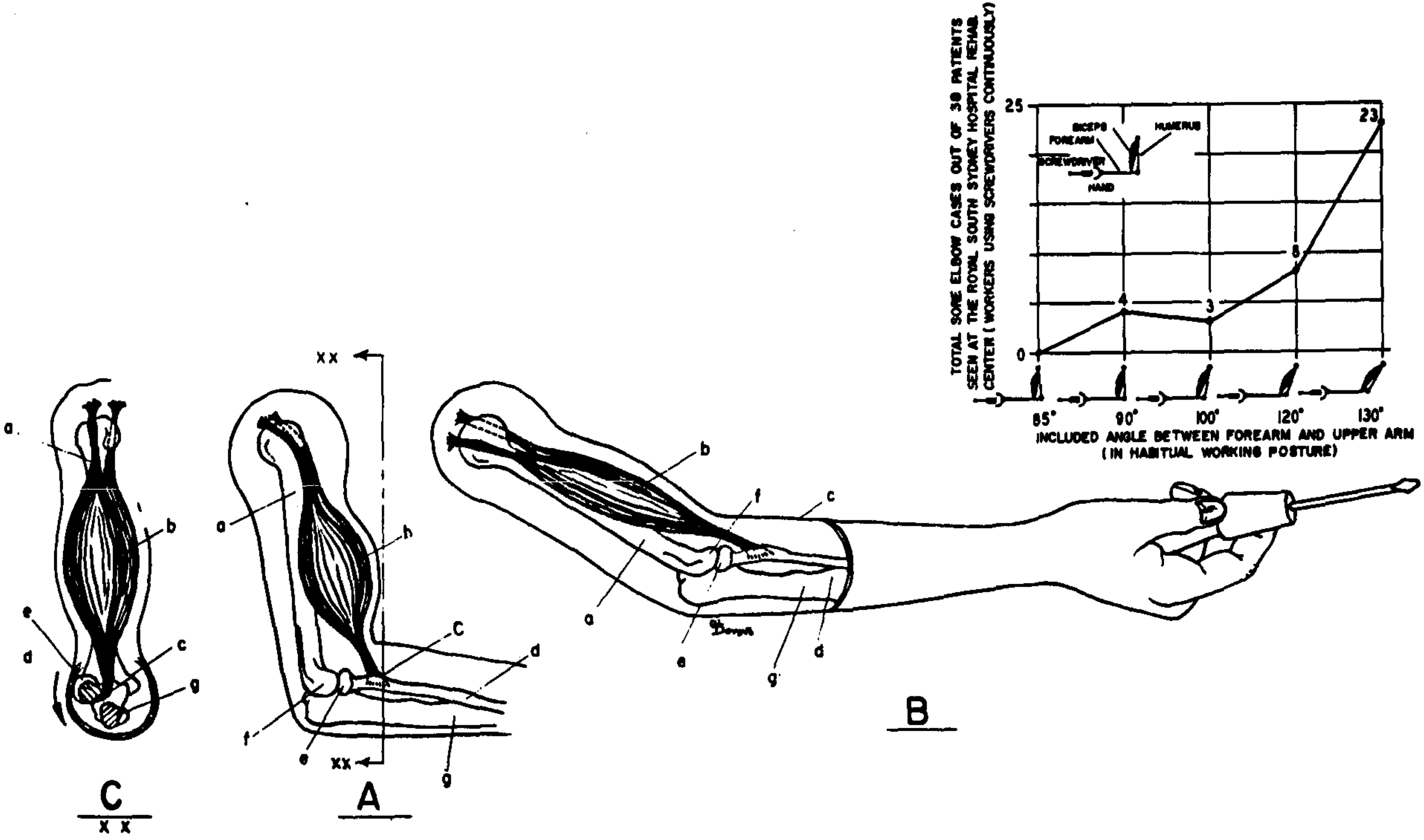
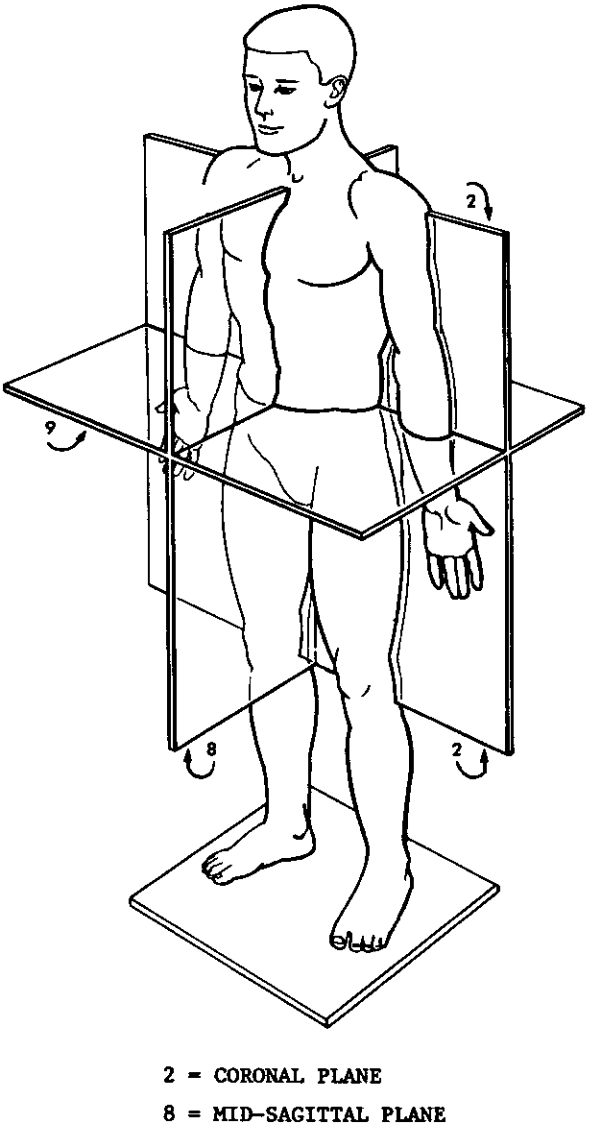


Figure 32-11. THE MECHANICAL ADVANTAGE OF THE BICEPS DEPENDS ON THE ANGLE OF FLEXION OF THE FOREARM. This muscle is not only a flexor, but also, due to the mode of attachment, the most powerful outward rotator of the limb. The worker who sits too far away from his work place has to overexert himself when using a screwdriver because the biceps operates at mechanical disadvantage. Sore muscles and excessive friction between the bony structures of the elbow joint are the results.[18]

In most cases anthropometry is concerned with the measurement of relationships between visible anatomical surface landmarks. In industrial practice, most data are obtained by direct caliper measurement. The data gathered are statistically evaluated and made representative of the range of body measurements typical for the working population under study. To substitute means in lieu of ranges is a dangerous practice. Often a piece of equipment of a workplace dimensioned for average man will be too small for one-half of the working population, and too large for the other half. Likewise, due consideration should be given to the substantial differences in body dimensions as well as skeletal geometry of movement between males and females.



Jacob, S. W., Francone, C. A.: Structure and Function in Man. Philadelphia, W. B. Saunders Co., 1970, p. 8.

Figure 32-12. The Basic Planes of Reference for Biomechanical and Anatomical Description[22].

**Industrial Seating**

Many jobs require performance in seated posture. Therefore, chairs are among the most important devices used in industry. They determine postural configuration at the workplace. Poorly designed seating accommodations represent frequent and definitive occupational hazards. Well-designed working chairs do not only contribute to the physical well-being of the working population but also may add as much as approximately 40 productive minutes to each working day. Optimal dimensions for working chairs and benches are well established and can be obtained with ease from standard reference works (Fig. 32-12).[21, 22] Numerical dimensions are of but limited value to the designer or user of industrial seating, unless they are supplemented by adequate knowledge of the relevant anatomical facts and biomechanical considerations.

To facilitate description of seated as well as other work situations based on anthropometric considerations, a uniform nomenclature of planes of reference suitable for the description of postures has been agreed upon by convention.[13, 23] A line in the coronal plane passing through the point of contact between the ischial tuberosities and the seating surface constitutes the "axis of support" (Figure 32-13) of the seated torso. This produces a "2-point support." Therefore, all coronal sections of the seating surface of the chair should be straight lines. A coronally contoured seating surface may restrict postural freedom at the workplace severely and, when poorly matched to the curvatures of the buttocks, may cause discomfort. Likewise, improper contouring may interact with sanitary napkins and other devices worn by women during the menstrual period with the ensuing further reduction in physical well-being during an already trying time of the month.

Working chairs should be "cambered" in the sagittal plane. The term "camber" describes the backward slant of the seating surface. A properly cambered seat prevents forward sliding of the buttocks and encourages the use of the backrest. A rough texture of the seating surface further helps to prevent undesirable and fatiguing sliding. The frontal end of the seating surface should terminate in a "scroll" edge which does not cut into the back of the leg. Finally, the seating surface should be preferably porous or else constructed in such a manner as to permit adequate conduction of heat away from the contact area between buttocks and chair. Especially undesirable are interacting combinations of multiple layers of loose garments made from synthetic fabrics and solid synthetic seat covers of, for example, vinyl plastic which will definitely affect female workers detrimentally due to a considerable damming up of heat at the body surface.

At the back of the leg, in the hollow of the knee, a sharp and easily distinguishable crease is located which is termed the "popliteal crease." The distance from the popliteal crease to the floor when standing in a relaxed upright posture and

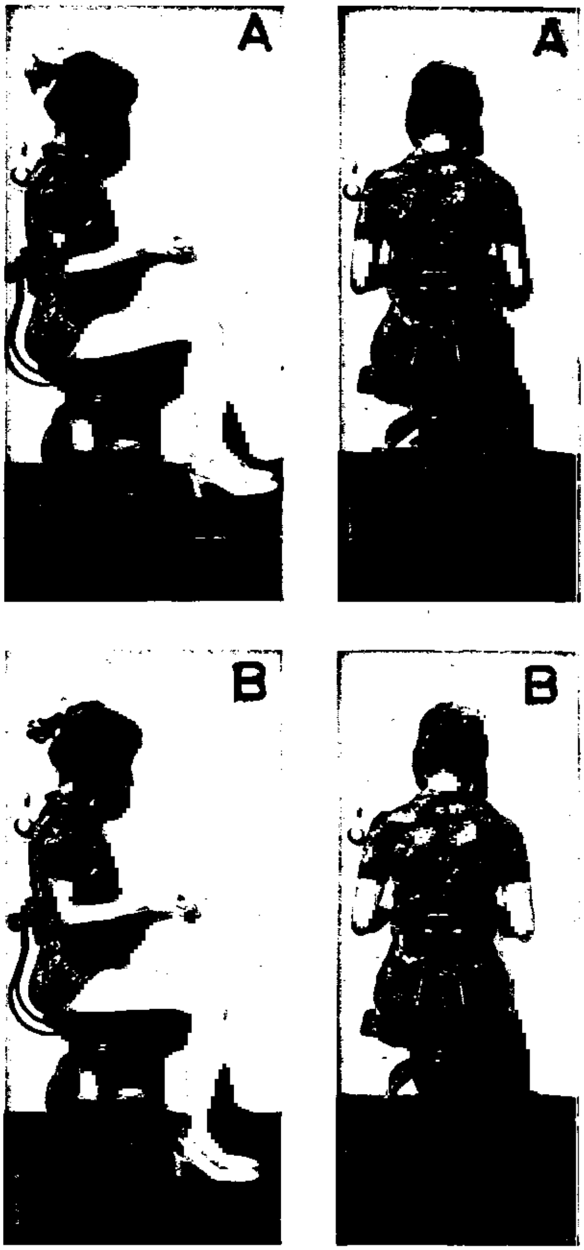


Figure 32-13. A biomechanically — correct seating posture (A) contributes substantially to health, well-being and efficiency of the working population. When the popliteal height of the worker is less than the popliteal height of the chair (B) discomfort will ensue. Note deformation of thigh and buttocks in situation (B).

while normal working shoes are worn is termed the "popliteal height *of the individual.*" The height of the highest point of the seating surface above the floor is the "popliteal height *of the chair.*" If the popliteal height of the chair is equal or greater than the popliteal height of the individual concerned, then undesirable pressures may be exerted upon the back of the thigh. To be comfortable, the popliteal height of the chair should be approximately 2-inches lower than the popliteal height of the individual. The seating surface should be short enough so that the distance between the front edge of the seat and the popliteal crease is about 5 inches. This dimension is called "popliteal clearance." In some industrial chairs, the depth of the seat can be regulated by adjustment of the backrest. If the backrest is moved forward, then the seat becomes shorter. This is a very desirable design feature contributing both to productivity as well as physical well-being.

The lower border of the backrest should clear the iliac crest. Preferably the upper edge or the highest point of contact with the back of the seated individual should be at a level lower than the inferior margin of the rib cage. At least the top of the backrest should clear all but the "false" ribs. Many work situations require continuous and rhythmic movement of the torso in the sagittal plane, and then a backrest which is too high will produce bruises on the backs of a considerable portion of the working population. The best designed backrests are small, kidney shaped, and can swivel freely about a horizontal axis located in a coronal plane. Thus, they fit well into the hollow of the lumbar region and provide the needed support for the lower spine without detrimental interference with soft tissues. It is often desirable, especially when much movement of the torso during work must take place, that the area of contact with the backrest does not extend beyond that region of the back which overlays the tough and fibrous plate which constitutes the origin of a large muscle; the latissimus dorsi. A backrest which is overly wide, under circumstances when much materials-handling and twisting of the torso in the seated position takes place will make frequent and repeated contact with the breasts of female workers.[24] This can produce great pain, especially during the premenstrual period when the breasts of many individuals are quite tender. Whenever backrests produce either bruising or only slight discomfort, workers protect themselves. The painful effects of excessive interaction between chair and torso are commonly reduced by ad hoc devices such as pillows, brought from home and strapped to the backrest. Work sampling studies show that several hours every week may be wasted in an effort to keep such improvised cushioning devices in place. Properly designed backrests are much cheaper than improvisations, both in the long as well as in the short run.[25]

A frequent and sometimes dangerous response to chair-generated discomfort is temporary absenteeism from the workplace. When the level of personal tolerance has been exceeded, workmen simply "take a walk." It is found occasionally that individuals involved in accidents are at the place of injury without authorization. Since no accident is possible unless victim and injury-producing agent meet at the same spot and at the same time, temporary absenteeism from the workplace may result in unnecessary exposure to potentially hazardous situations.[7]

Some working chairs are equipped with coasters. These facilitate limited locomotion and materials-handling without abandoning the seated posture. In many work situations, coasters help to reduce unnecessary torsional moments acting on the lumbar spine. In other circumstances, especially in some cases of circulatory disturbance in the lower extremity, a chair equipped with coasters may stimulate muscular activity and consequently improve circulation in the leg. However, coasters should only be used when they either contribute to the well-being of an individual or the efficiency of an operation. They constitute some hazard to safety. There is always the risk that the chair rolls accidentally away or is inadvertently removed while the user gets up for a brief interval of time. Where possible, a cheap restraining device such as a nylon rope, a chain, or, in some circumstances, a rigid linkage between chair and workbench should be considered.

Supervisors as well as workers should receive brief but formal instruction in the proper adjustment of working chairs. First, the height between seating surface and top of the workbench is adjusted so that an optimal angle of abduction of the upper arms during activity can be maintained. The chairs should have design features permitting easy adjustment in discrete steps. A 3-step height adjustment is adequate for most populations and in most situations. Secondly, after the height of the seat with respect to the top of the worktable has been fixed, correct popliteal height is then established by means of an adjustable footrest. Footrails, because they cannot be easily adjusted, are less desirable, and may traumatize anatomical structures around the ankle joint and may interfere with the ease of access to foot pedals. Occasionally drawers located underneath workbenches may interfere with proper seat height adjustment and should then be removed. There should be no need for adjustment of the camber in a well-designed working chair. Third, seating surfaces should be wide enough to permit some postural freedom. Arm rests are sometimes useful but in some situations, support for only one arm is needed. In such case, a chair with detachable arm rests should be provided.

No one single chair design can possibly fit all work situations. Seating analysis should always be conducted in a thorough fashion, giving due weight to all relevant features of the task under consideration. It is highly desirable that standard reference works[19,21,22] be available during consultation.

In addition to the analysis of the seated posture with respect to physical comfort and biomechanical correctness, it is also necessary to consider the changes in kinesiology of the lower extremity resulting from seated posture. The seated leg and foot can rotate only with diffculty and unless the popliteal height of the chair is extremely low, such as is the case in motor vehicles, operation of foot pedals may become cumbersome and fatiguing. On the other hand, the seated "leg and thigh aggregate" can abduct and adduct voluntarily, precisely and strongly without fatigue for long intervals of time. It is therefore frequently advantageous to make use of this kind of movement in the design of machine controls (e.g., the knee switch of the sewing machine). In the seated posture, knee switches are generally superior to foot pedals.

### The Physical Dimensions of the Workplace

In most industrial enterprises, productive activities are organized according to certain principles of division of labor and thus broken down into a series of relatively simple and specific operations; each one assigned to a different employee. Therefore, most members of the working population do spend practically the entirety of their productive time confined to a quite small area of the manufacturing plant which is termed "the workplace." Thus, in many instances the term "workplace" is synonymous with "working environment" and includes everything except man himself. Thus, regular as well as protective clothing, climate, illumination, chairs, machines, tools, and the product worked upon must be considered in the ergonomic analysis of the industrial environment. Within the narrower framework of biomechanics, the physical relationship, in terms of distances and other linear dimensions is often of paramount importance to production efficiency as well as to physical and emotional well-being of the worker. Even small changes in the dimensions of the workplace may have large effects on occupational safety and health as well as on the economics of the productive process.

In practice, the designer of workplaces must often operate within the constraints of accepted industrial standards. These aim at the attainment of maximal levels of production efficiency. Most of these standards were developed between 1917 and 1936.[26,27] Unfortunately, the development of industrial standards relating to the dimensions of the workplace lags behind the development in workforce and technology which has so radically altered the industrial environment during the last few years. Acceptance of recommended changes in workplace layout will normally depend on the ability of the analyst to convince all parties concerned that higher levels of efficiency accompanied by increased well-being are a normal "by-product" of work situations dimensioned to suit the anthropometric and kinesiologic capabilities of the workforce.

Perhaps the most commonly used set of "norms" for workplace layout are the "Principles of Motion Economy" which were first enunciated by the Gilbreths,[28] improved by subsequent researchers and accepted today generally in the format developed and presented by Barnes[29] who uses as a subheading for that table the words "A Checksheet for Motion Economy and Fatigue Reduction" (Table 32-1). Many of these principles of motion economy are still applicable in the form in which they were originally enunciated. However, others have become either redundant or, in some instances, outright hazards to safety and health. They were devised to optimize the interaction between man and the workplace within the framework of technologies and industrial furniture available at the time of their conception. They aim principally at an increase of produc-

## TABLE 32-1

### Principles of Motion Economy

*A Check Sheet for Motion Economy and Fatigue Reduction*

These twenty-two rules or principles of motion economy may be profitably applied to shop and office work alike. Although not all are applicable to every operation, they do form a basis or a code for improving the efficiency and reducing fatigue in manual work.

*Use of the Human Body*

1. The two hands should begin as well as complete their motions at the same time.
2. The two hands should not be idle at the same time except during rest periods.
3. Motions of the arms should be made in opposite and symmetrical directions, and should be made simultaneously.
4. Hand and body motions should be confined to the lowest classification with which it is possible to perform the work satisfactorily.
5. Momentum should be employed to assist the worker wherever possible, and it should be reduced to a minimum if it must be overcome by muscular effort.
6. Smooth continuous curved motions of the hands are preferable to straight-line motions involving sudden and sharp changes in direction.
7. Ballistic movements are faster, easier, and more accurate than restricted (fixation) or "controlled" movements.
8. Work should be arranged to permit easy and natural rhythm wherever possible.
9. Eye fixations should be as few and as close together as possible.

*Arrangement of the Work Place*

10. There should be a definite and fixed place for all tools and materials.
11. Tools, materials, and controls should be located close to the point of use.
12. Gravity feed bins and containers should be used to deliver material close to the point of use.
13. Drop deliveries should be used wherever possible.
14. Materials and tools should be located to permit the best sequence of motions.
15. Provisions should be made for adequate conditions for seeing. Good illumination is the first requirement for satisfactory visual perception.
16. The height of the work place and the chair should preferably be arranged so that alternate sitting and standing at work are easily possible.
17. A chair of the type and height to permit good posture should be provided for every worker.

*Design of Tools and Equipment*

18. The hands should be relieved of all work that can be done more advantageously by a jig, a fixture, or a foot-operated device.
19. Two or more tools should be combined wherever possible.
20. Tools and materials should be pre-positioned whenever possible.
21. Where each finger performs some specific movement, such as in typewriting, the load should be distributed in accordance with the inherent capacities of the fingers.
22. Levers, crossbars, and hand wheels should be located in such positions that the operator can manipulate them with the least change in body position and with the greatest mechanical advantage.

From "Motion and Time Study", R. M. Barnes, John Wiley & Sons, Inc., New York, 1963.

tive output per unit of time with fatigue reduction and maintenance of product quality a secondary, albeit important, consideration.

A second set of universally used, as well as misused, schemes of "normal" and "extended" reach and work areas[29] must be considered limited in application as the schemes neglect anthropometric considerations necessary due to different ethnic compositions of diverse working populations. They also neglect age and are based on an incorrect conception of the kinesiology of the upper limb.

However, there is still very much substance in the "Principles of Motion Economy," the concepts of work areas, predetermined motion-time systems as well as other current industrial standards; they are still useful and, when properly applied, of great potential value for the promotion of economic efficiency as well as occupational health. To adapt the above-mentioned industrial systems, standards and practices to current needs, the dimensions of the workplace should comply with the following set of rules:[30]

*Rule 1*: The dimensions of the workplace are determined by body measurement as well as range and strength of movement of the kinetic elements involved in a task. These should be obtained from reference works specifically aiming at the industrial environment.[31]

*Rule 2*: Workplaces should always be dimensioned to suit the full range of body measurements of that specific working population likely to be assigned to the task under consideration.[32]

*Rule 3*: Differences of sex, ethnic origin and educational or social background often express themselves in specific types of musculo-skeletal configurations as well as specific motion inventories and/or manipulative skills. Therefore, both dimensions as well as geometry of the workplace should take these characteristics into consideration if maximal efficiency and physical well-being are to be obtained in competitive situations.

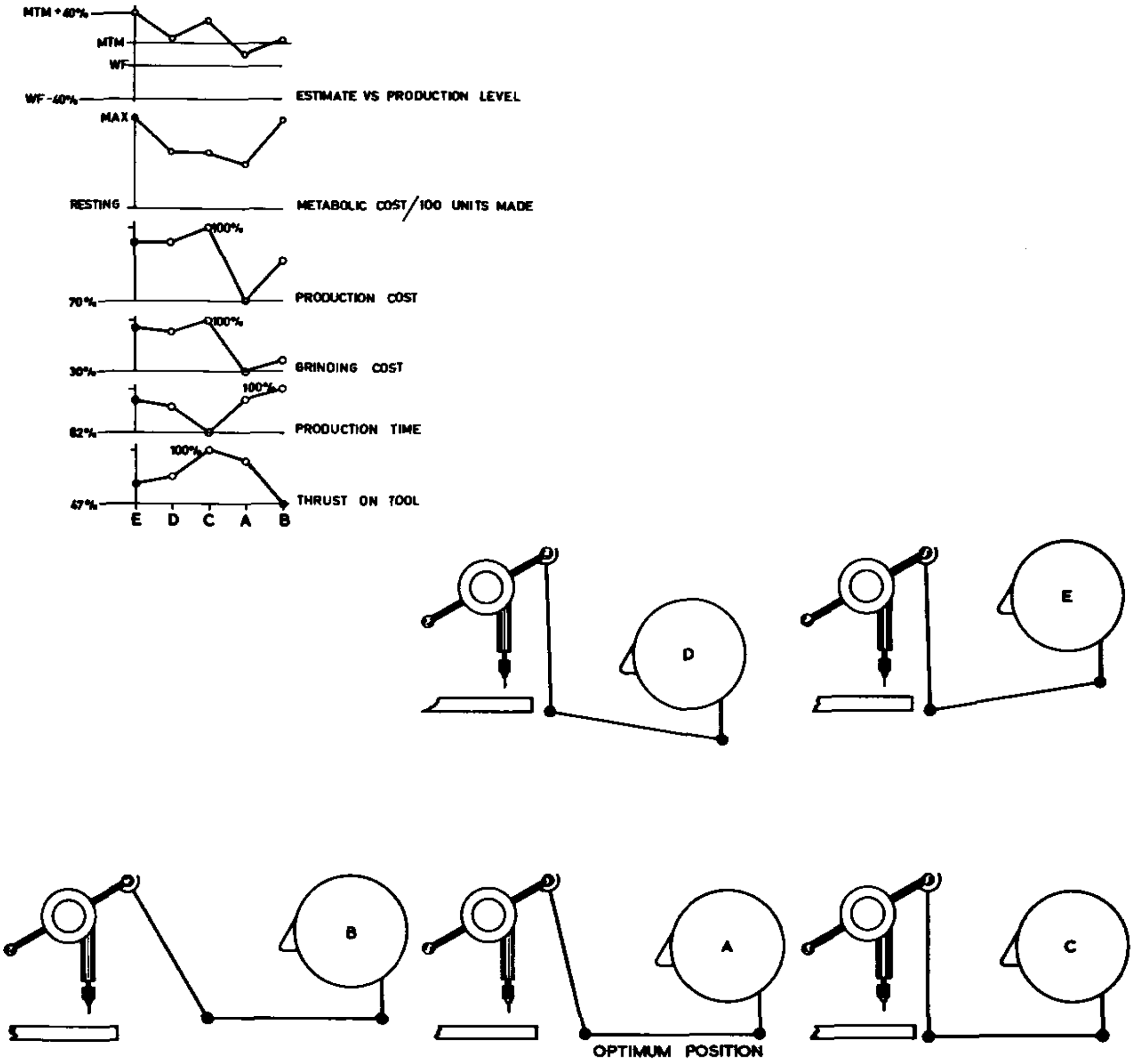


Figure 32-14. If the dimensions of equipment do not suit the body measurements of workers, then displacement by as little as 2 inches from the optimum position of the operator may modify performance levels of man and/or equipment considerably.

*Rule 4*: Optimal position of operator with respect to equipment controls should be ascertained by biomechanical analysis. Relatively small deviations from the optimum may produce drastic productive as well as physiological responses from the equipment operator (Figure 32-14). Therefore, both operator and supervisor should receive instructions about proper positioning of individuals with respect to the physical features of the workplace.

*Rule 5*: In repetitive work situations, task design should aim at maximal postural freedom. Wherever feasible, a task should be equally well-performable in the seated as well as the standing posture. Such occasional changes during the working day are beneficial and therefore measurements of workbenches, chairs, trays, equipment, etc., should be selected in such a manner as to permit individuals to stand up or sit down without changing the angle of abduction of the upper arm, the angle of forward flexion of the upper arm, or the included angle between forearm and upper arm (Figure 32-15).

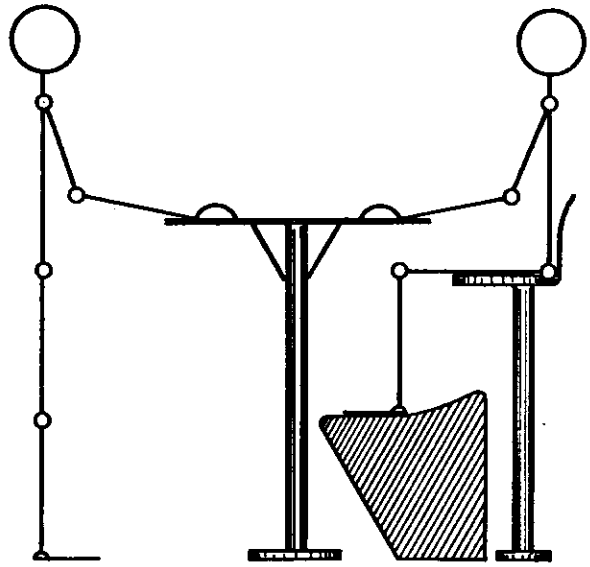
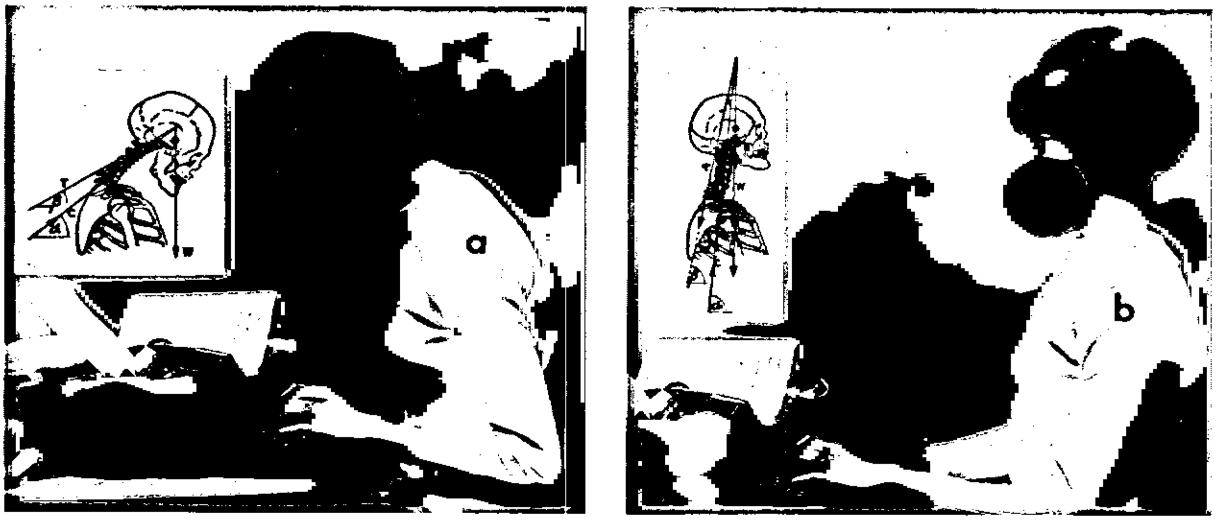


Figure 32-15. When work is possible in either seated or standing position, then workbench and seating design should permit change of posture without change of musculo-skeletal configuration.

*Rule* 6: In work situations demanding a standing posture, all tasks, including materials-handling operations, should be performable without standing on the toes, torsion or sideways bending of the trunk.

*Rule* 7: No work should be performed on a strip 3" wide from the border of the workbench which is closest to the operator. The proximity of this area to the operator's body demands excessive retraction or abduction of the upper arm to bring the hands into position. In addition, excessive forward flexion of head and neck are needed to achieve effective eye/hand coordination (Figure 32-16). Under such conditions, users of spectacles or individuals afflicted with slight arthritic conditions of the neck, who are frequently found in middle-aged and other working populations, can suffer considerable physical discomfort. Likewise, in many women, the position of the breasts interferes with ease of visual scanning in this area.

*Rule* 8: Whenever workplaces must be designed on the basis of already accepted standardized normal and extended reach areas (Figure 32-17), then this information should be supplemented by charts which display optimal directions within each area and identify such points as may be difficult to reach due to anatomical or kinesiological reasons.[33]



Tichauer, E. R.: Industrial Engineering in the Rehabilitation of the Handicapped. J. Ind. Eng. XIX:96-104, 1968.

Figure 32-16. (A & B) Visual problems combined with bad postural habits might cause a typist to sit too close to the typewriter. This may put great strain on a neck with arthritic lesions (a). To educate the patient to sit eight inches further away from the typewriter helps to reduce stress on the cervical spine and assists with problems caused by farsightedness (b). Compressive stress between the sixth and seventh cervical vertebrae in "a" is approximately three times the force computed for "b."

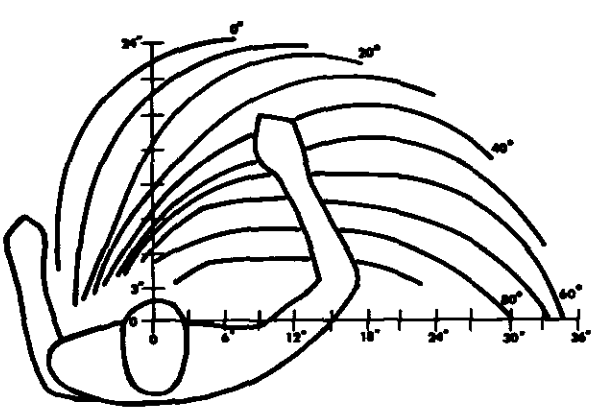


Figure 32-17. The natural motions pathway of the wrist changes with the angle of abduction. Adapted from (33).

*Rule 9*: The dimensions of areas for temporary holding or storage of products in process should be computed on the basis of queuing theory. Frequently the following formula can be used to advantage:[8]

$$N = \frac{\text{Log } P}{\text{Log } R}$$

where N = the required capacity of the area

P = the greatest acceptable probability that the area will become temporarily overloaded. This number is normally determined on the basis of a subjective management decision.

R = the mean arrival rate of units per time divided by the mean processing rate. These values are normally available from the Motion and Time Studies Department.

*Rule 10*: Source of incident or reflected light should be located in such a manner as not to produce visual discomfort due to glare (Figure 32-18).

## WORK TOLERANCE

Within the context of Ergonomics, *work stress* is defined as any action of an external vector upon the human body while *work strain* manifests itself as the physiological response to the application of stress.[34] Stress and strain need not occur at the same points. An increase in environmental temperature above normal is correctly called "heat stress" and the resulting increase in sweating rate is then identified as "heat strain." Likewise, when lifting loads, the force exerted upon the musculoskeletal system is termed "work stress" and the resulting increases of cardiac and metabolic activity are each examples of "work strain."

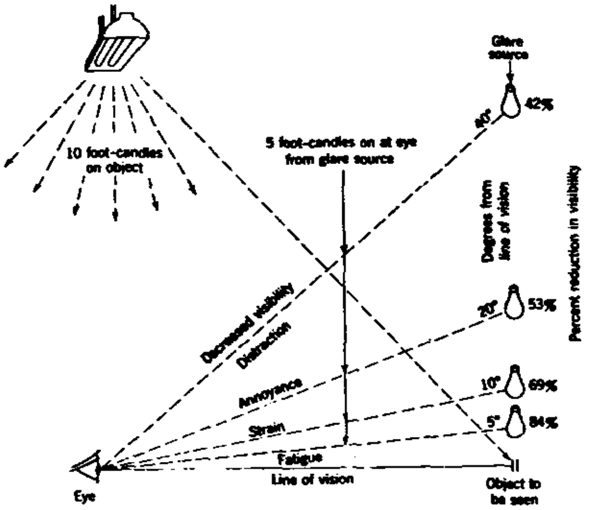


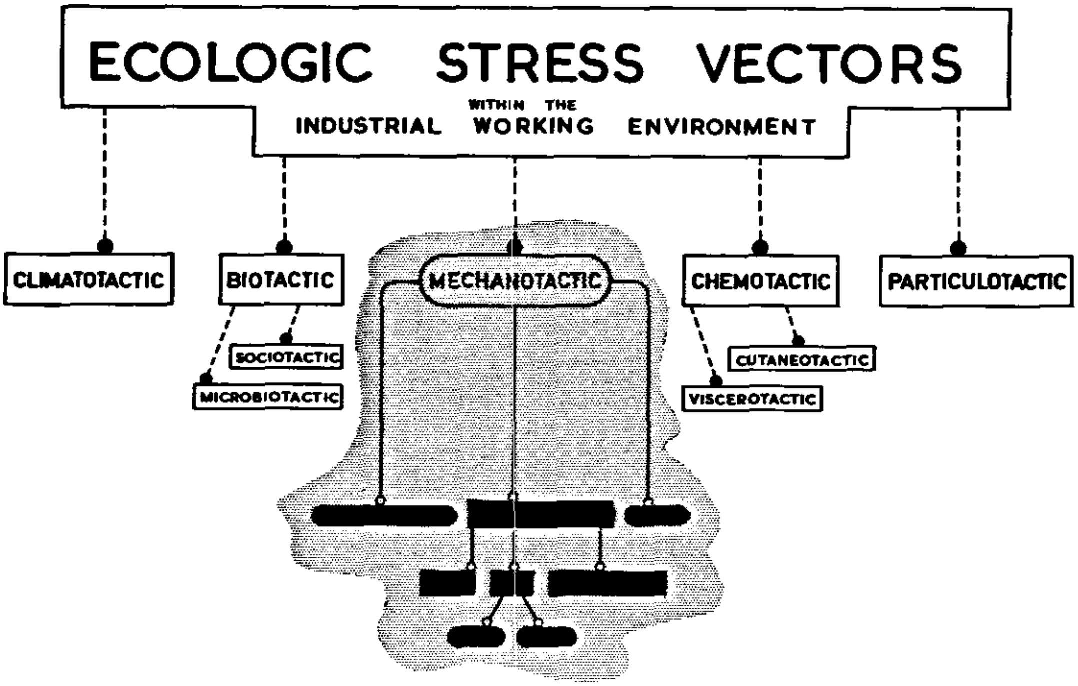
Figure 32-18. Glare becomes worse as it comes closer to the direct line of vision. From M. Luckiesh, *Light, Vision and Seeing*, copyright 1944, D. Van Nostrand Co., Princeton, New Jersey.

The performance of any task, no matter how light, will impose some work stress and consequently by needs elicit physiological responses characteristic of work strain. Thus, neither work stress nor work strain per se are undesirable; unless they become excessive and produce work-induced disease or diminished work tolerance. The general field of Ergonomics is concerned with five basic environmental stress vectors (climatotactic, biotactic, mechanotactic, chemotactic, particulotactic) (Figure 32-19).[35] All but mechanotaxes are treated comprehensively elsewhere in this book. Therefore, only mechanotaxes, contact with things mechanical, is discussed in this chapter.

Mechanotactic stress results in three types of strain (Fig. 32-20):

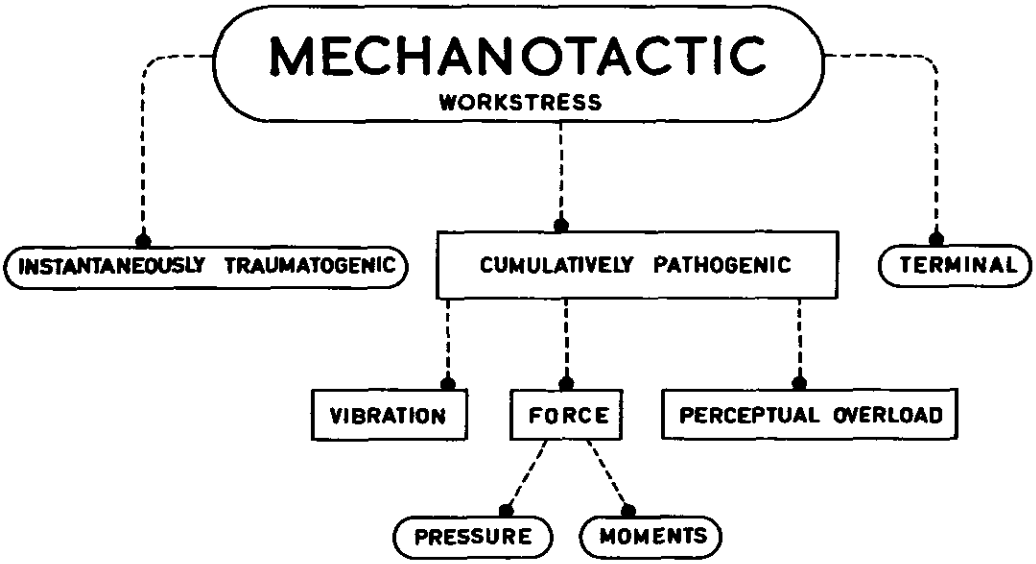
1. Terminal Strain: Death.
2. Instantaneous Trauma: An immediately apparent physical injury.
3. Cumulative Pathogenesis: The gradual development of ergogenic disease by repeated mechanotaxis applied for sufficiently long intervals of time; where each individual application of stress may be quite harmless in itself, but produces lesions through frequency and repetition of application.

Contact with things mechanical, even light contact, may result in trauma. A long enough stay in bed may produce a very intractable lesion, the bed sore. Writer's cramp and the calluses on the hands of surgeons are other well-known examples of strain resulting from mechanotactic stress. Often excessive environmental stress leads to a reduction in work tolerance, long before injury or disease have become manifest. The establishment of conditions conducive to high levels of work tolerance is of utmost importance for the maintenance of occupational health.



Tichauer, E. R. Potential of Biomechanics for Solving Specific Hazard Problems. Proc. 1968 Professional Conference, American Society of Safety Engineers, Park Ridge, Illinois, 1968, pp. 149-187.

Figure 32-19 The Scheme of Ecologic Stress Vectors Common to All Working Environments. Workstress is derived from contact with climate, contact with living organisms such as fellow man or microbe, contact with things chemical, contact with hostile particles such as silica, or asbestos and finally, contact with things mechanical.[35]



Tichauer, E. R. Potential of Biomechanics for Solving Specific Hazard Problems. Proc. 1968 Professional Conference, American Society of Safety Engineers, Park Ridge, Illinois, 1968, pp. 149-187.

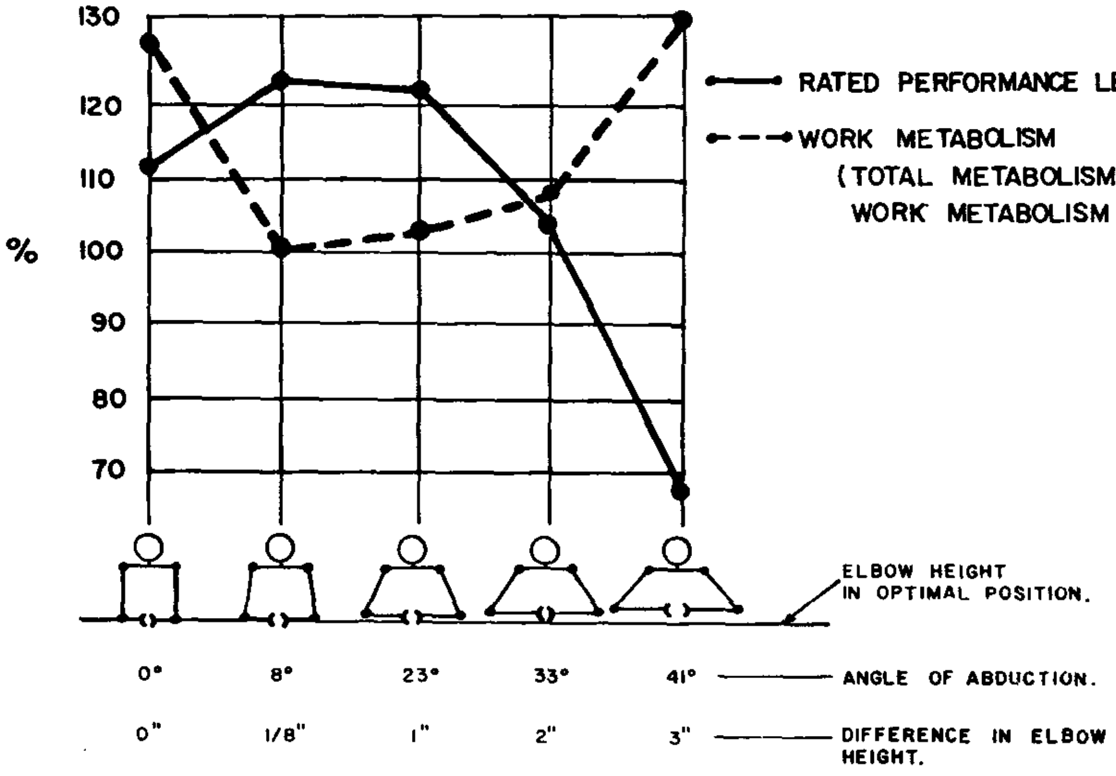
Figure 32-20. Mechanotactic Stress Vectors Leading to Hazard Exposure in the Industrial Environment: A. Instantaneous Traumatogenesis (e.g. an arm is torn off). B. Terminal (e.g. death occurs immediately). C. Cumulative Pathogenesis. This term describes the gradual development of disability or disease through repeated exposure to Mechanical Stress Vectors over extended periods of time.[35]

## TABLE 32-2

## Prerequisites of Biomechanical Work Tolerance

by E. R. Tichauer

| *Posture*: | *Man-Equipment Interface*: | *Effective Kinesiology*: |
|---|---|---|
| (P1): Keep the elbows down. | (E1): Do not restrict circulation. | (K1): Avoid deviation of the wrist while moving or rotating the forearm. |
| (P2): Keep moments acting on the vertebral columns low. | (E2): Vibrations transmitted at the man-equipment interface should not lead to somatic resonance reactions. | (K2): Avoid forward reaches exceeding 16 inches. |
| (P3): Avoid Covert Lifting Tasks. | (E3): Moving parts of the body should not be constrained by rigid supports. | (K3): When the motion element "transport loaded" has to be performed in the sagittal plane, then the movement should be directed towards the body and not away from it. |
| (P4): Scanning should require eye movement only and not necessitate simultaneous head motion. | (E4): Stress concentration on small skin areas or small joints should be avoided. | (K4): Holding and manipulation are mutually exclusive operations. |
| (P5): A musculo-skeletal configuration conducive to maximal biomechanical efficiency should be maintained. | (E5): Ergonomic check-lists should always be consulted whenever handtools are designed, modified, selected or evaluated. | (K5): Motions should be terminated by positive external stops rather than by voluntary muscular action. |



Tichauer, E. R. Potential of Biomechanics for Solving Specific Hazard Problems. Proc. 1968 Professional Conference, American Society of Safety Engineers, Park Ridge, Illinois, 1968, pp. 149-187.

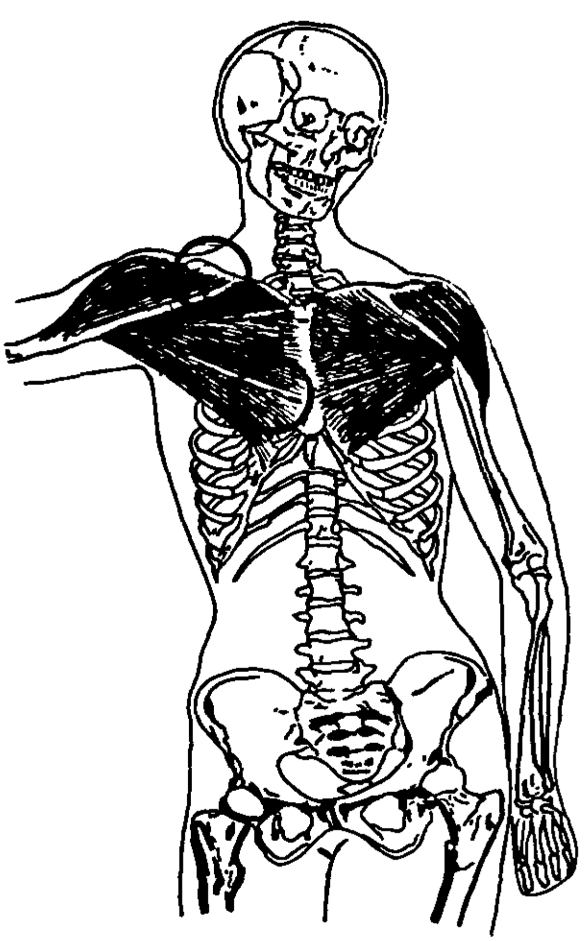
Figure 32-21. Effect of Angle of Abduction on Physiological As Well As Economical Working Efficiency of 12 Female Workers 20 to 32 Years of Age Engaged in Food Packing. Stick figures indicate elbow height in relation to optimal position (horizontal line); first line of numerals, angle of abduction, in degrees; bottom line, difference in elbow height, in inches, from optimal position, statistically tested means are reduced to arbitrarily fixed "benchmarks" of 100 percent. Work metabolism (total metabolism minus work metabolism, dashed line) measured by Wolff's method and instrument Performance levels (solid line).[35]

### Work Tolerance

Work tolerance is defined as the ability to perform a task at acceptable economic levels with respect to both quality as well as quantity of output, while, at the same time, enjoying a full measure of physiological and emotional well-being.

The most important prerequisites of Biomechanical Work Tolerance are presented in tabular form (Table 32-2), arranged into three sets each consisting of five "Prerequisites":

P: Five prerequisites relating to the maintenance of postural integrity and safety.
E: Five prerequisites relating to the development and maintenance of nontraumatogenic man/equipment interfaces.
K: Five prerequisites relating to the production of an effective as well as nonfatiguing kinesiology.



Tichauer, E. R. Potential of Biomechanics for Solving Specific Hazard Problems. Proc. 1968 Professional Conference, American Society of Safety Engineers, Park Ridge, Illinois, 1968, pp. 149-187.

Figure 32-22. Keeping the arm abducted brings large muscles into play. This, during protracted periods of work, may cause soreness over chest and shoulder in some untrained individuals and therefore occasionally induce fear of heart disease or even an impending heart attack. Areas of potential soreness are circled.[35]

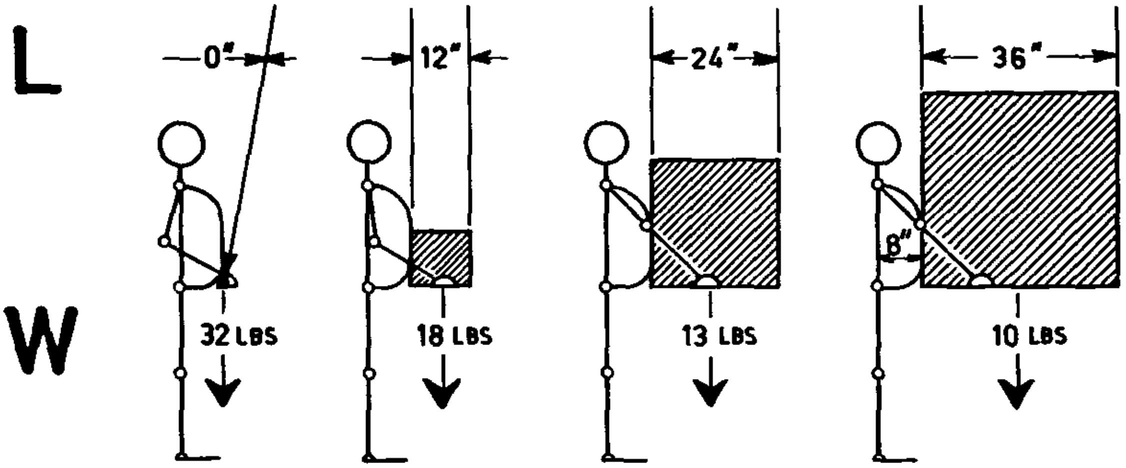
### Posture

P1: *Keep the elbows down.* Unnecessary abduction of the upper arm, especially if maintained for extended periods of time, may have several undesirable side effects. It may also be produced through carelessness in workplace design in several different ways. For instance, if chair height is poorly policed, then a seat height only three inches too low with respect to the work surface will produce an angle of abduction of the upper arm of approximately 45° (Figure 32-21).[36, 37] When this is the case, then a wrist movement at the workplace normally performed by rotation of the humerus would require a physically demanding shoulder swing. The resulting fatigue over several hours may reduce the efficiency rating by as much as 50%. Also when the seat is too low, especially in assembly operations, the left arm is frequently used as a vise, and the right hand to manipulate objects. Then after an hour or two, particularly under incentive conditions, some vague sense of discomfort over the origin of the left pectoralis and deltoid muscles, which stabilize the abducted arm, may be felt. This can lead especially in elderly and overweight workers, or those with heart conditions, to an unjustified fear of an impending heart attack and all the ensuing undesirable emotional difficulties (Figure 32-22).

P2: *Keep moments acting on the vertebral column low.* Lifting stress is not solely the result of the weight of an object handled. Its magnitude must be expressed in terms of "Biomechanical Lifting Equivalent" in the form of a "moment." This relationship, when holding a load upright, can be roughly estimated by taking 8 inches as the thickness of the human body plus half the length of the load, again in inches. The sum will approximate the distance of the center of mass of the load from the lumbar spine. Very often a light but bulky object (Figure 32-23) may impose a heavier lifting stress than a heavy load of great density.

P3: *Avoid covert lifting tasks.* Physiologically a lifting task exists when, for any reason whatsoever, a moment is applied to the vertebral column. This frequently includes situations where only body segments are moved but no object is lifted (Figure 32-24). Then man becomes an analog of the crane and the same mechanical considerations with respect to load supporting capacity apply to both. When bending over, the weight of the body segment moved — in this case, the trunk — may impose a far greater lifting stress than the load itself. Likewise, there are work situations where everything is stacked high and closely arranged in semicircular fashion around the worker. This requires holding up of the arm and thus applying a torque on the shoulder joint for extended periods of time. This may produce pain in the lumbar region because the torque is transmitted through the stabilized shoulder via the vertebral column onto the lumbo-sacral joint. Other examples will be discussed in a separate section on back problems.

P4: *Scanning should require eye movement only and not necessitate simultaneous head motion.* Only under conditions of binocular vision is it possible to estimate correctly and/or easily true



$$\left(8+\tfrac{1}{2}L\right)(W)=M_{\epsilon}\approx 250\ \text{INCHPOUNDS}$$

Tichauer, E. R.: Potential of Biomechanics for Solving Specific Hazard Problems. Proc. 1968 Professional Conference, American Society of Safety Engineers, Park Ridge, Illinois, 1968, pp. 149-187.

Figure 32-23. The "Moment Concept" Applied to the Derivation of Biomechanical Lifting Equivalents. All of the loads represented in the figure produce approximately equal bending moments on the sacro-lumbar joint (approximately 250 inch pounds). 8 = approximate distance in inches from the joints of lumbar spine to front of abdomen (i.e., a constant for each individual). L: length in inches of one side of a cube of uniform density lifted during the standard task. W: the weight in lbs the cube handled. Me: the biomechanical lifting equivalent (here approximately 250 inch pounds).[35]

or relative distances or sizes of objects. Binocular vision without head movement can take place only within a cone of 60° included angle, the axis of which is originating from the root of the nose and is located in the midsagittal plane of the head (Figure 32-25). Often head movement at the workplace constitutes a "protective" reaction necessary to reestablish binocular eyesight whenever the visual target is located outside of the cone. Simultaneous eye and head movements take much time, and this may produce a hazard whenever fast-moving equipment (motor vehicles, airplanes, conveyors) are operated. Furthermore, whenever head movement is restricted (e.g., eyglasses or arthritic lesions in the neck), then if objects of manipulation are located outside the visual cone of 60°, problems of eye-hand-head coordination will ensue.

P5: *A musculo-skeletal configuration conducive to maximal biomechanical efficiency should be maintained.* Unless the individual members of a kinetic chain involved in the performance of a task are optimally positioned and aligned, with respect to each other as well as with any equipment controls employed, considerable work strain may result, even under conditions of light work. Of especial importance in this respect are angles formed between long bones (Figures 32-11 & 32-14).

**Man-Equipment Interface**

E1: *Do not restrict circulation.* Both the designer as well as the evaluator of tools and equipment should be familiar with the location of the principal and vulnerable blood vessels. Otherwise circulation may be inadvertently impaired and localized ischemia can result. Of especial importance is the protection of the blood vessels in the hand. For example, a poorly designed or improperly held scraping tool (Figure 32-26) may squeeze an important blood vessel, the palmar arch, between handle and the hamate bone. Numbness and tingling of the fingers will follow.

E2: *Vibrations transmitted at the man-equipment interface should not lead to somatic resonance reactions.* White Finger Syndrome, or intermittent blanching and numbness of the fingers, sometimes accompanied by lesions of the skin, has been identified for many years as an occupational disease associated with the operation of pneumatic hammers and other vibrating tools.[38, 39] Vibrations of low frequency and quite low intensity can make the whole body, body segments or individual viscera vibrate at harmonic resonance frequencies.[40] The resulting symptoms may simulate a wide range of musculo-skeletal and organic diseases such as back pain, respiratory difficulties, cardiac distress or minor ailments such as visual disturb-

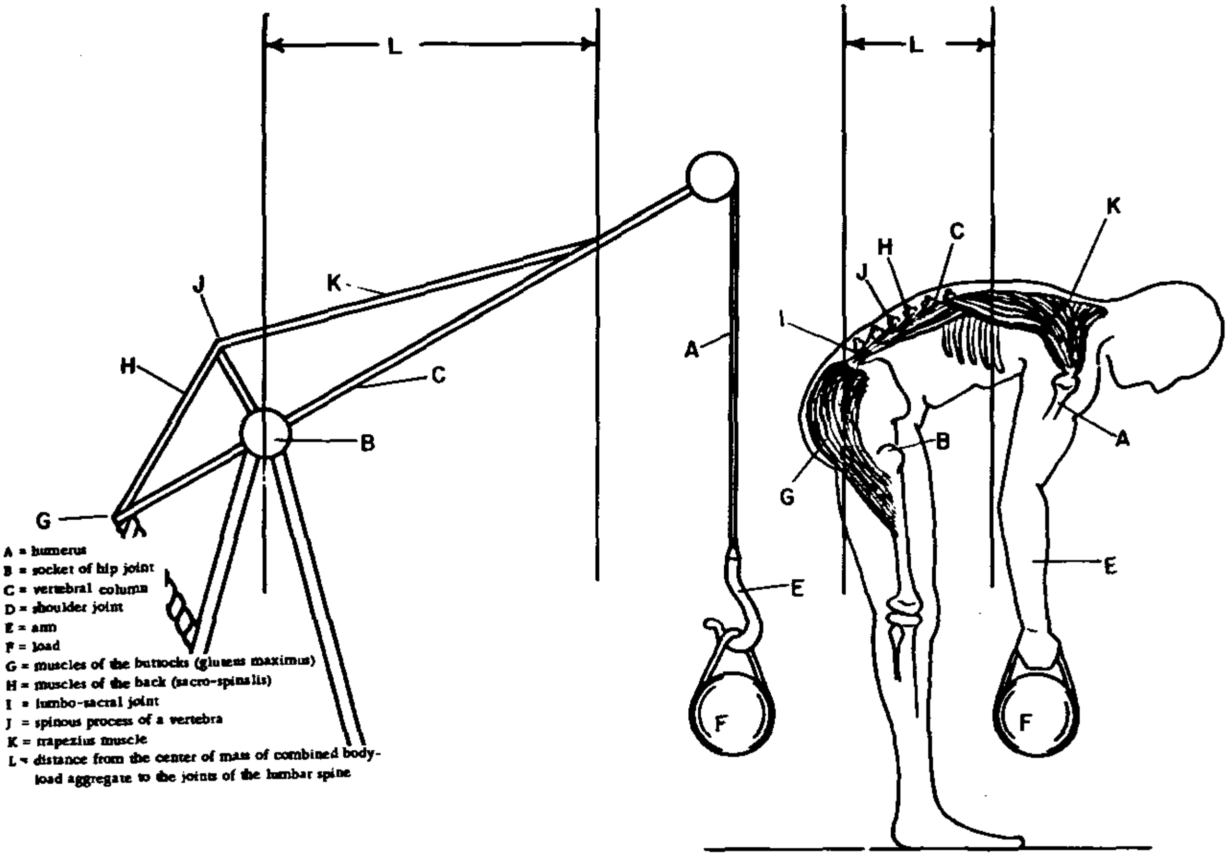


Figure 32-24. IN LOAD-LIFTING, THE STRUCTURAL ELEMENTS OF MAN ARE ANALOGOUS TO THE STRUCTURAL ELEMENTS OF A CRANE. The same mathematical techniques can be applied to predict performance of either of them.[18]

ances.[41] Reliable literature[42] and experienced expert advice should be consulted whenever vibration transmittal between equipment and the human body is a possible cause of manifestations of ill health.

E3: *Moving parts of the body should not be constrained by rigid supports.* Where extensive movement of the trunk in the sagittal plane is required, an improperly located backrest will produce bruises. Likewise, a firm arm rest supporting a moving elbow will lead to swelling and inflammation.

E4: *Stress concentration on small skin areas or small joints should be avoided.* In many industries a trend towards miniaturization, mechanization and automation is conducive to the ever-increasing introduction of highly localized work stress. Often simple remedies will help to prevent penetration of the skin, calluses, or the aggravation of joint disease. The tailor's thimble is one good example. Often the introduction of simple cushioning devices such as foam rubber or springs underneath pushbuttons can reduce or eliminate trauma to the distal interphalageal joints of the fingers. Even the prevention of soreness of the fingertips may facilitate or accelerate training programs for the technologically obsolescent in a pushbutton-oriented society. Finally, formfitting handtools or equipment handles often fit only one hand perfectly: the hand of the designer. When used by individuals with larger or smaller hand dimensions, contour features may cut into the body surface and produce localized stress concentrations.

E5: *Ergonomic checklists should always be consulted whenever handtools are designed, modified, selected or evaluated.* The most frequent, as well as most intense, contact between man and equipment occurs normally at the handtool interface. The design features of a nontraumatogenic handtool are complex and an ergonomic checklist is presented as a separate section of this chapter.

### Effective Kinesiology

K1: *Avoid deviation of the wrist while moving or rotating the forearm.* Tools are occasionally designed in such a manner as to demand deviation of the wrist towards the ulna or the radius during operation (Figure 32-27). This affects both health as well as efficiency. The principal flexor and extensor muscles of the fingers originate in the elbow region and are connected with the phalanges by way of long tendons. The extensor tendons are held in place by a confining transverse ligament on the dorsum of the wrist while the

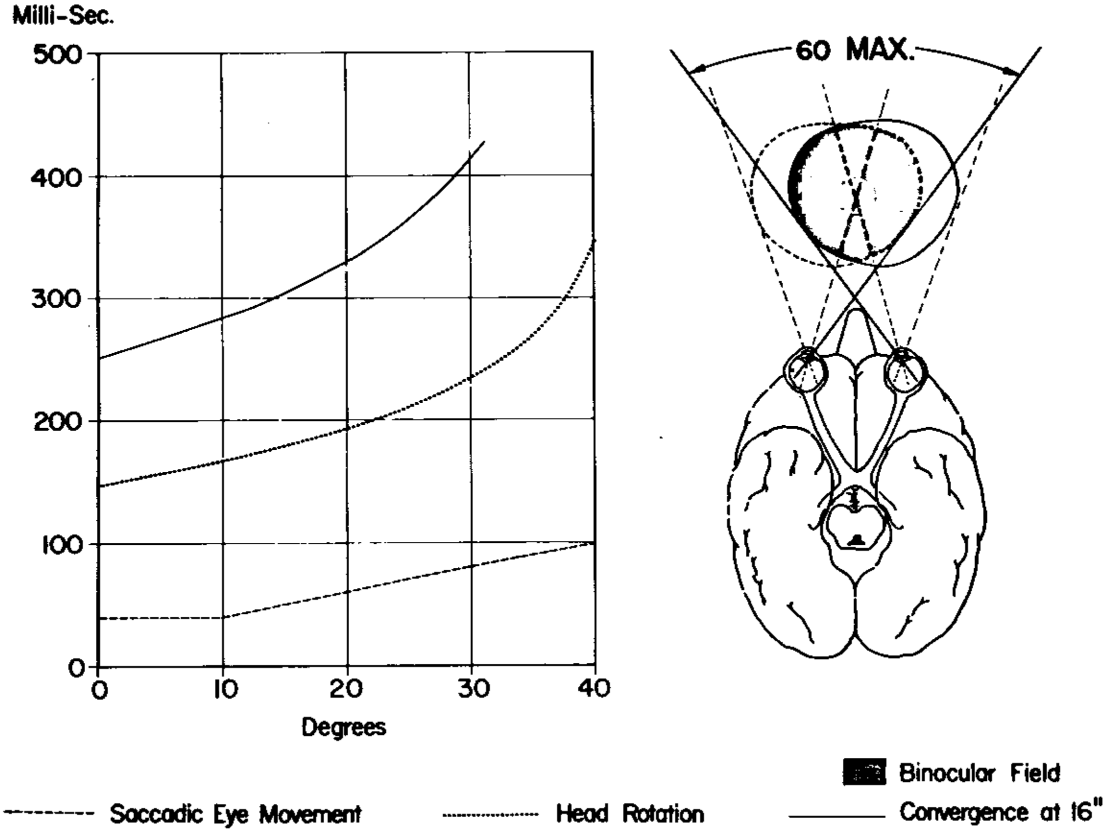
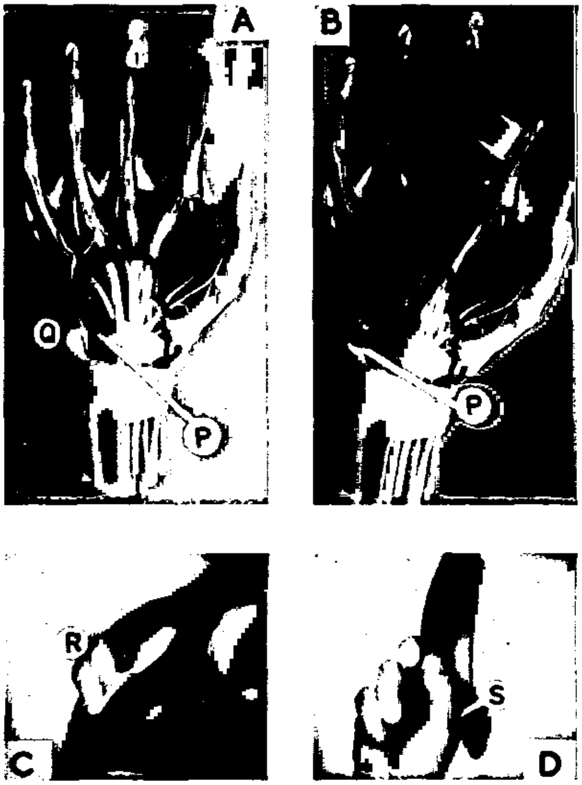


Figure 32-25. "EYE TRAVEL AND BINOCULAR VISION" (RELATED TO SPEED AND QUALITY OF PERFORMANCE).

flexor tendons on the palmar side of the hand pass through a narrow carpal tunnel which contains also the median nerve. Deviation of the wrist towards the ulna causes these tendons to bend and to become subject to mechanical stress underneath the ligament and in the tunnel. This is conducive to tenosynovitis. Likewise, this skeletal configuration favors ulnar drift of the extensor tendons which is highly undesirable when a hand is already afflicted with even very light arthritis. When such a tool is used in jobbing operations for only a few minutes every working day, then generally no ill effects are experienced. However, when continuous operation under production conditions is demanded, ulnar deviation constitutes a hazard to the health of the working population, and it should be remembered that it is much safer to bend the tool than to bend the wrist. If, however, ulnar deviation is overcompensated so that the wrist becomes deviated towards the radius, then the hazard of "tennis elbow" is introduced. This risk is particularly high when a work situation demands the simultaneous dorsiflexion and radial deviation of the wrist. Furthermore, deviation of the wrist reduces the range of rotation of the forearm and hand (Figure 32-28). As much as 50% of the useful range of motion may be lost through wrist deviation. Whenever screws have to be inserted or panels wired, the number of wrist movements necessary to perform that task will have to be doubled because of the lost range of motion. This is conducive to early fatigue and difficulties during training.

K2: *Avoid forward reaches exceeding 16 inches.* Most systems of predetermined motion times in common use in industry for the purposes of workplace layout postulate that reach time is a linear function of reach length.[43] This, however, applies only to young individuals with a high degree of physical fitness. In a middle-aged working population, where the vertebral column exhibits already the signs of the normal wear and tear of life, in woman during the premenstrual and menstrual period, and in individuals afflicted with light arthritic conditions of the vertebral column, a reach in the sagittal plane exceeding 16" constitutes a severe covert lifting task and causes reach time to increase proportionally to the square of the reach length (Figure 32-29). Under such conditions, certain groups of workers will not only be at a competitive disadvantage, but will suffer severe physical discomfort when trying to keep up with younger and more physically-fit workers. It is often easy to arrange the workplace in such a manner as to obviate excessive reach length.

K3: *When the motion element "Transport Loaded" has to be performed in the sagittal plane, then the movement should be directed towards the body and not away from it.* The protagonist muscles of forward flexion of the upper arm oper-



Tichauer, E. R.: Ergonomics: The state of the art. Amer. Ind. Hyg. Assoc. J. 28:106-16, 1967.

Figure 32-26. Ergonomic Considerations in Hand Tool Design. A, the relations of bones, blood vessels, and nerves in the dissected hand. B, a paint scraper is often held so that it presses on a major blood vessel (P) and directs a pressure vector against the hook of the hamate bone (Q). C, in the live hand, this results in a reduction of blood flow to, among others, the ring and little fingers, which shows as a darkening on infrared film (R). D, a modification of the handle of the paint scraper causes it to rest on the robust tissues between thumb and index finger (S), thus preventing pressures on the critical areas of the hand.[7]

ate at biomechanical disadvantage. Their antagonists are the large and powerful muscles of the back and this, in balance within the kinetic element, makes a sagittal forward reach per se an undesirable motions element. The transport of even a relatively light object, by means of the hand away from the body in the direction of the sagittal plane leads to early fatigue, loss of precision of movement and ultimately great discomfort in the shoulder region. Such disposal movements are best performed at an angle of 45° to the sagittal plane or in the coronal plane (Figure 32-30). K4: *Holding and manipulation are mutually exclusive operations.* The arrangement of muscles, tendons and ligaments which make possible the use of the hand for "work" is complex. The fully flexed wrist, among other reasons because of pretensing of the extensors of the fingers, does not permit an effective wraparound grasp (Figure 32-31).[44] Under opposite conditions, when the wrist is fully hyper-extended, the configuration of the wrist joint, tension in the flexor muscles of the fingers, and the mechanical disadvantage of the small intrinsic muscles of the hand, do not permit the effective use of the distal phalanges for fine manipulative movements.

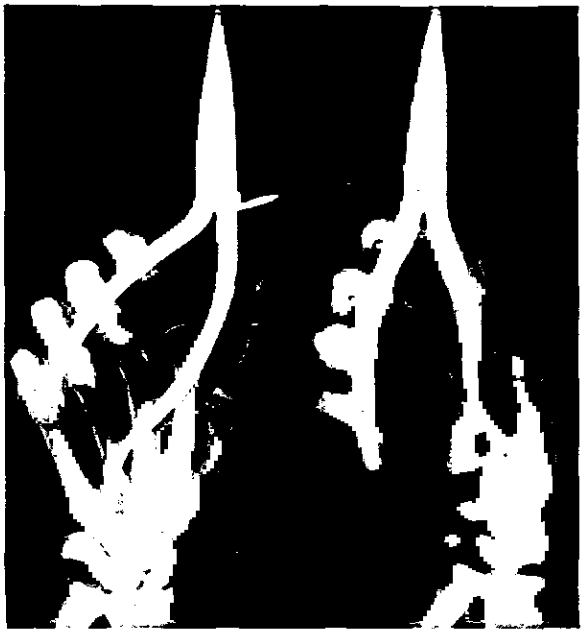


Figure 32-27. STRAIGHT-NOSE PLIERS PRODUCE STRONG BENDING MOMENTS IN THE WRIST. Neither the axis of rotation nor the axis of thrust correspond with the corresponding axes of the limb. A tool with a bent nose eliminates these faults.[18]

When the wrist is fully extended, but not hyper-extended, there is 100 percent grasping power, 50 percent holding power, and 50 percent manipulative effectiveness. In full flexion of the wrist, the hand is 100 percent effective in manipulation but has almost no holding power.

The strong dependence of the effectiveness of the hand on skeletal configuration may produce situations where a machine control can be tightened or loosened effectively by a right-handed person, but can be completely unmanageable by a left-handed one. Often such job difficulties for left-handed people may be eliminated by creating a work situation without postural restraint as far as the wrist is concerned. Whenever a task requires a mixture of both holding and manipulation such as is frequently the case in the operation of vises, fixtures, dials to be adjusted, then these controls should be located so that they can be operated effectively by both the right as well as the left hand. Often a simple bend in a lever or the positioning of a dial at an angle will accom-

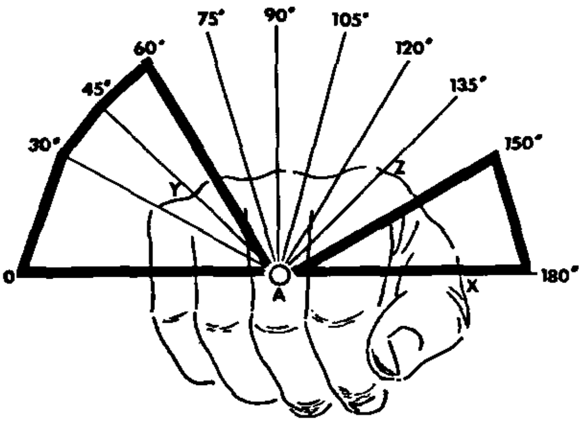


Figure 32-28. Ulnar deviation of the wrist reduces normal range of pronation-supination from 180 degrees to 90 degrees, thus doubling the number of movements necessary to perform a pronation-supination task. Fatigue or, even worse, occupational trauma may ensue. (Adapted from Industrial Engineering Handbook: H. B. Maynard, editor, McGraw Hill Book Co., 1963. p. 5-23).

plish this. About 25% of the working population are left-handed.

K5: *Motions should be terminated by positive external stops rather than by voluntary muscular action.* It is well-known that termination of hand movement with precision, especially when high speed is demanded or incentive conditions are involved, can lead to performance difficulties. Well-known systems of predetermined motion times make allowance for a "positive stop work factor," recognizing the need to facilitate the precise termination of hand movements by positive contact with an external stop. This important sensory facilitation can be achieved through diverse, physically quite different devices (Figure 32-32). In each and every case it will reduce the need for voluntary control over precision of movement and often will reduce performance times. This is of especial importance to the young worker who is inexperienced, those with little innate manual dexterity and the elderly who are developing tremors or show the beginnings of not yet clinically important bone and joint disease. Especially under incentive conditions, or where the possibility of dismissal because of failure to meet efficiency demands exists, these working populations may develop emotional reactions such as nervousness, or abrasiveness, in contact with fellow workers unless sensory facilitation produced at positive stops enables them to perform again at competitive levels. Not infrequently the absence of positive stops produces intense nervousness, especially when the job security of a worker depends on his ability to maneuver a fragile object into a narrow space. Such physiological responses may include fluctuations and increases of heart rate and variations in respiratory parameters.

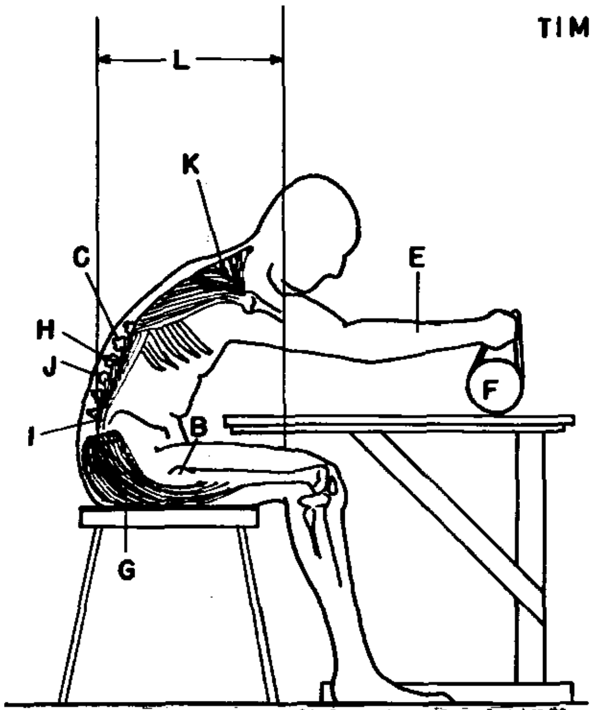
Not all of the above-listed "Prerequisites of Work Tolerance" are applicable to all work situations and all individuals. They provide, however, a convenient checklist for the analysis of existing or planned work situations in order to insure that human needs for peace of mind, physical comfort, occupational safety and health have not been sacrificed for the sake of short-term expediencies such as the need to maintain high performance speed over short periods of time. Where the majority of prerequisites of work tolerance are applied (Table 32-2), there is a better labor-management relationship. Likewise, improvement of the general physical and emotional health of the working population as well as an increment in economic efficiency, and higher levels of product quality will be observed.

## HANDTOOLS

The basic tools used today by man as well as the basic machines were invented in the dawn of the prehistoric age and evolved over many thousands of years. However, the contemporary and very rapid rate of industrial and technological development demands frequently "instant" creation of new and specialized implements through efficient design rather than by evolution. This section considers both hand tools as well as equipment controls since the latter are merely the "tools" which permit the operation of machinery. Also, the functions of tools are varied and their shapes diverse. There are many principles of biomechanics and ergonomics which need to be considered in the selection and evaluation of almost all kinds of tools, no matter how different their fields of application. Some of the material presented here has been mentioned elsewhere in this chapter. It is, however, by no means redundant, as such repetition where it occurs, emphasizes the relevance of ergonomic and biomechanical factors upon the selection and evaluation of the most commonly used implements in industry, tools and equipment controls.

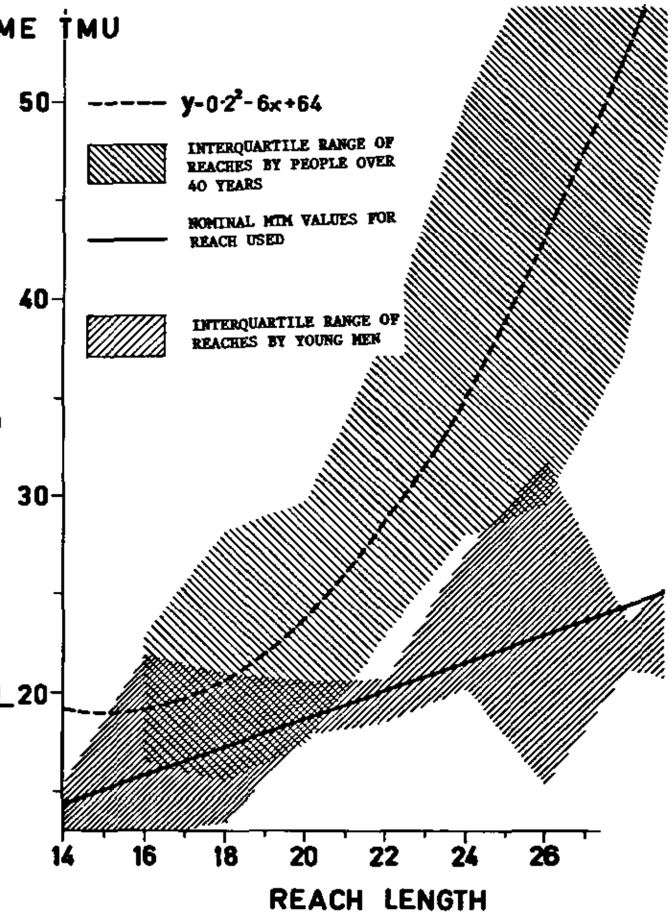
### Force Optimization

The prime purpose of primitive tools was to transmit forces generated within the human body onto a material or workplace. In the course of artisanal and industrial development, this purpose was widened so that tools should now be designed to extend and reinforce range, strength, and effectiveness of limbs engaged in the performance of a given task. The term "extend" as used here is not restricted to the meaning of magnification and amplification because often a tool makes possible a far finer movement than the unarmed hands would be capable of performing (e.g., tweezers, screwdriver) and sometimes it enables the application of a grip or grasp soft enough so as not to injure a workpiece as is the case in a suction tool so often used to transport small and fragile components. A micromanipulator of the "master-slave" type is another good example of a tool which serves as an attenuator rather than as an amplifier of human force and motion.



Awareness of the "Hidden" Lifting Task Should Exist. Because of Higher Torques Exerted on the Lumbar Spine, a Seated Job, Instead of Being "Light Work," May Be the Physiological Equivalent of a Severe Lifting Task. In Seated Work, the Rule Is: "Get the Job Close to the Worker." (Adapted from(43)

A = Humerus
B = Socket of Hip Joint
C = Vertebral Column
D = Shoulder Joint
E = Arm
F = Load
G = Muscles of the Buttocks (Gluteus Maximus)
H = Muscles of the Back (Sacro-Spinalis)
I = Lumbo-Sacral Joint
J = Spinous Process of a Vertebra
K = Trapezius Muscle
L = Distance from the Center of Mass of Combined Body-Load Aggregate to the Joints of the Lumbar Spine



Tichauer, E. R.: Industrial engineering in the rehabilitation of the handicapped. J. Ind. Eng. XIX:96-104, 1968.

Figure 32-29. The Interquartile Range of 1200 Reaches in Sagittal Direction Performed by Individuals above 40 Years of Age Fitted Well to a Quadratic Equation. A control experiment where a like number of reaches was performed by young men showed agreement with MTM data. A system of predetermined motion times for the elderly worker remains still to be developed.

In an endeavor to provide maximum mechanical advantage, equipment designers frequently maximize through effective use of the principle of the lever, the ratio of force output from the tool divided by the force input from the hand. This, however, can be easily overdone, because the force output should also provide sufficient sensory feedback to the muscular-skeletal system in general and the tactile surfaces of the hand in particular. In a thread-tapping job, for instance, if this ratio is too large, the force applied may be excessive resulting in either stripped threads or broken taps and bruised knuckles. If, on the other hand, the ratio of force output over force input is too small, then an unduly large number of work elements will have to be repeated to complete a job such as is the case in the pounding of a large nail with too small a hammer. A tool should also produce an optimal stress concentration at a desired location on the workpiece. Thus, up to a certain limit, an axe should be as finely honed as possible to fell a tree with the minimum number of strokes, but the edge should not be so keen as to require frequent resharpening or to be fragile.

Finally, the shape of the tool should be such as to insure that it is automatically guided into a position of optimal mechanical advantage where it will do its job best without bruising either hand or workpiece. The Phillips Screwdriver as compared with the ordinary flat blade tool is a good example of such efficient design.

**Distribution of Pressures and Stresses**

The use of handtools causes generation of a large variety of stress vectors at the man-equipment interface. These may be mechanical, thermal, circulatory or vibratory and have a tendency to be propagated to other points within the body. Thus, awareness that work strain and the resulting trauma often show up at points quite remote from the locus of work stress application must be

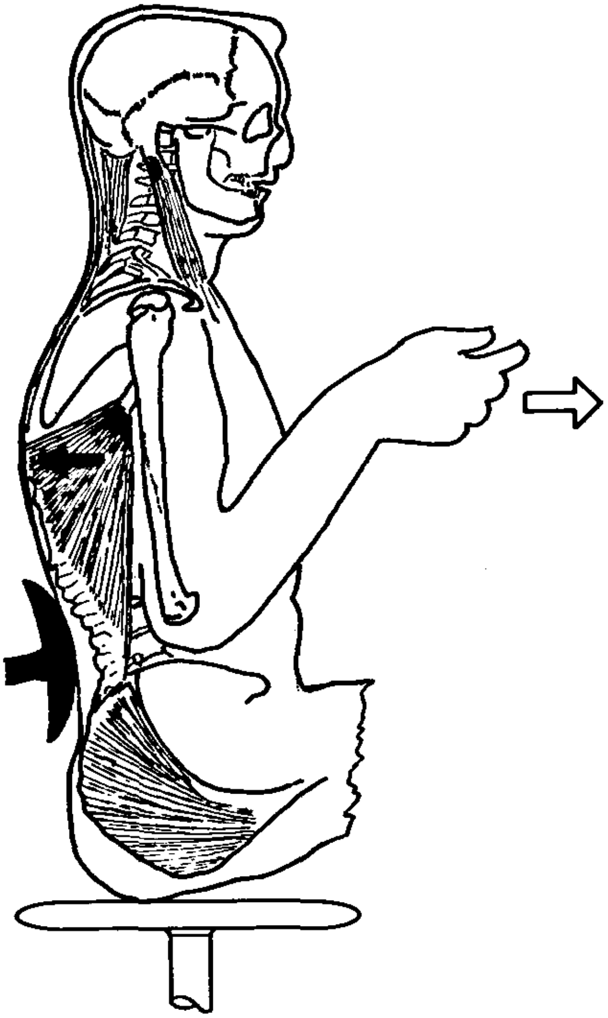


Figure 32-30. The disposal of objects in a direction away from the body and in the mid-saggittal plane is conducive to discomfort and early fatigue because of the strong antagonist activity in the latissimus dorsi muscle.

kept constantly in mind.[45] Contact surfaces between the tool and the hand or other live tissues should be kept large enough to avoid concentration of high compressive stresses. Pressures should be distributed over sufficiently large skin areas so that both ischemia as well as mechanical trauma to nerves are avoided. Care should be exercised to avoid all but the mildest possible compression against those areas of the hand which overlie particularly vulnerable blood vessels and nerves (Figure 32-33). "Form-fitting" should be a feature employed only sparingly in the design of handles and all anthropometric factors of relevance should be considered so that the handle does not fit only the hands of the designer properly. Likewise, it is advantageous to use the tough tissue located at the vertex of the angle formed between the spread thumb and index fingers as one of the skin areas capable of supporting large pressure and other physical stress.[46] Whenever finger grooving is employed as a device to facilitate firm gripping of a tool, then it should be shaped in such a manner as not to lead to stress concentration on the interphalangeal joints when oversized or undersized hands must hold the implement (Figure 32-34). Therefore, the selector and evaluator of handtools should be provided with and trained in the use of an atlas of the anatomy of the hand and be fully familiar with shape and location of those anatomical structures which relate to the long term and short term safety of handtool usage.

### Consideration of Working Gloves

Many undesirable results may stem from improper fit and/or design of working gloves. These may lead to low efficiency and certain health hazards; but a false impression may be generated that these discomforts, poor workmanship and increased tendency towards injuries, could be due to poor tool design. Unsuitable working gloves are likely to be associated with one or more of the following areas of concern resulting in handtool usage:

1. *Loose gripping of tools.* It is impossible to close the hand without causing the interphalangeal surfaces of the fingers to abut against each other (Figure 32-35). The skin between the fingers is particularly richly endowed with nerve end organs which transmit sensory feedback to the central nervous system. Strength of grip may well be dependent upon pressure between the fingers. If the working glove is too thick in this region, high pressures at the interdigital surfaces may be generated before the hand is firmly closed about the tool handle or equipment control and these may then be insecurely grasped. Awareness of this lack of firmness of hold may cause many individuals to grip unnecessarily tightly and firmly which results in increased fatigue and other undesirable side-effects. Also, if a working glove is too thick, the fingers may not be able to wrap around the handle sufficiently for a firm hold. The detrimental effect of overdesigned working gloves becomes most apparent when pulling cables or holding firmly onto smooth rods.
2. *Carpal tunnel considerations.* The carpal tunnel is a channel in the wrist through which important nerves, blood vessels and tendons pass into the hand (Figure 32-36). Pressure, generated by overly tight or too stiff cuffs of working gloves, on the tunnel itself or on the areas immediately proximal or distal to it may result in one or more of the following: ulnar tenosynovitis; impairment of blood supply to the hand and, consequently, coldness, numbness and tingling of the fingers. The fit of working gloves should be checked before tool design or workload are considered as a possible cause for the aforementioned symptoms. There is a well-known disease entity, the "carpal tun-

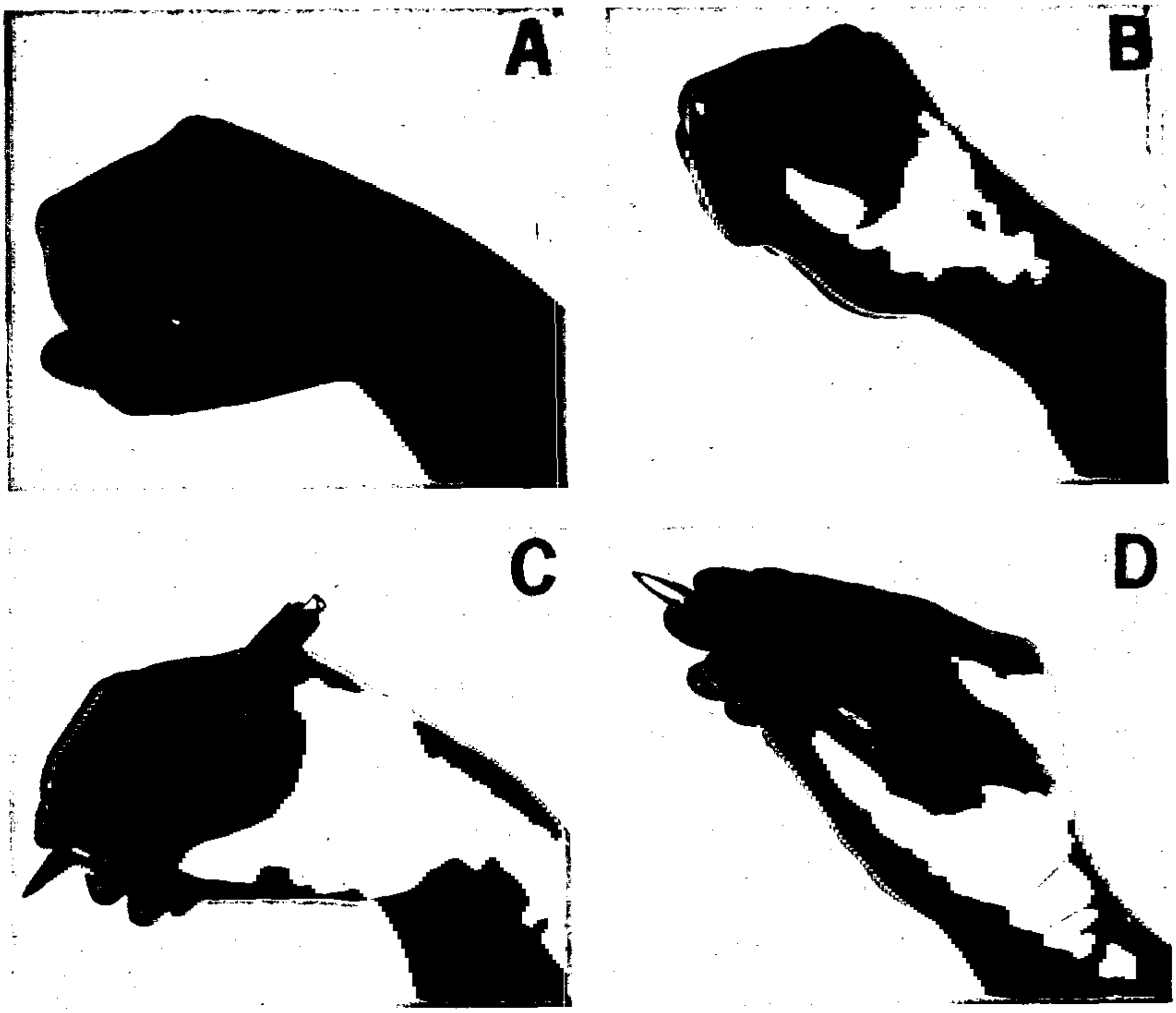


Figure 32-31. The flexed wrist (A) cannot grasp a rod firmly, while the straight wrist (B) can grip and hold firmly. Conversely the flexed wrist (C) is well positioned for fine manipulation, but when extended (D) freedom of finger movement is severely limited.

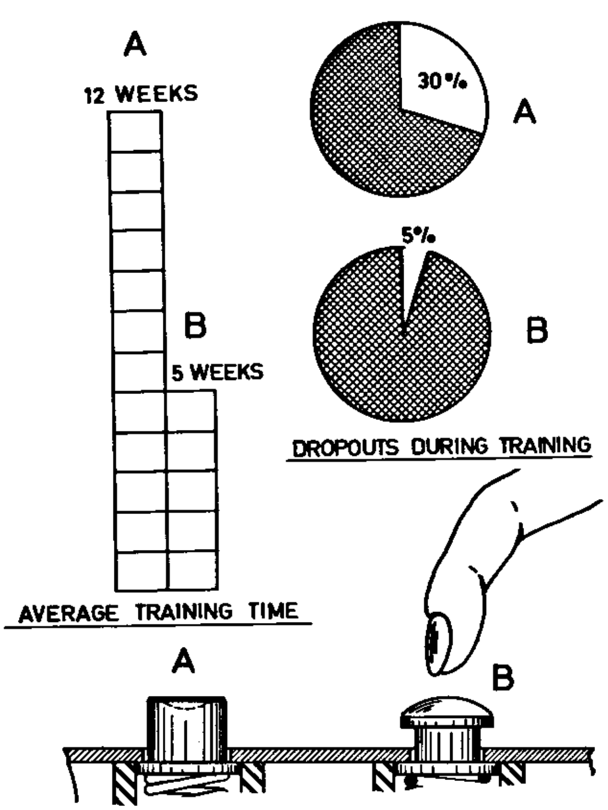
nel syndrome." This can be aggravated through poorly designed working gloves; but may not have been caused by either gloves, tools or workplace design.

**Selection and Evaluation of Tools Based on Biomechanical Design Considerations**

Repetitive maneuvers and the resulting cumulative work stress are far more frequent causes of occupational trauma than spontaneous overexertion.

Frequently observed in this connection is tenosynovitis. This may be due to biomechanical overstress or an infectious process. Both overuse of the hand as well as unaccustomed usage are associated with tenosynovitis and some consider it a "training disease." Industrial physicians often resort to a medically-imposed restriction of performance levels once the disease has been diagnosed.[47]

Tenosynovitis is most frequently observed on the back of the hand where it involves the extensor tendons. It is not a "training disease," but a definite sign of overstress which should be corrected by changes in tool design or workplace layout. Whenever changes in the design of the working environment and implements are not feasible, then reduction in task demands such as lowering the required output or changes in work rhythm should be considered as possible means to reduce tenosynovitis. As another alternative, "job enlargement"[48] may be tried. Then members of the exposed working population will not be performing the "suspect task" throughout the entire working day, but will be rotated periodically to workplaces which are less conducive to excessive cumulative work stress imposed upon the wrist. Equipment used under circumstances where repetitive rotation of the wrist against resistance is required should allow the task to be performed without ulnar deviation. Ulnar deviation favors



Tichauer, E. R.: Potential of Biomechanics for Solving Specific Hazard Problems. Proc. 1968 Professional Conference, American Society of Safety Engineers, Park Ridge, Illinois, 1968, pp. 149-187.

Figure 32-32. Sensory facilitation of positioning can be achieved in many ways, be it by enlargement of contact surfaces "B", or sometimes by the flairing of inlet holes. Such facilitation will result in the reduction of training time as well as in an increased number of individuals capable of learning a new operation without fatigue or discomfort. Adapted from (35).

"drift" towards the ulna of the extensor tendons, exposing these and the surrounding tendon sheath to compressive stresses. Likewise, on the palmar side of the wrist, those tendons, nerves and blood vessels which pass through the carpal tunnel are subjected to similar stresses in ulnar deviation (Figures 32-27 & 32-36).

A pre-existing risk of tenosynovitis, be it due to the anatomy of the operator, or due to working conditions, may be enhanced whenever strong palmar flexion of the wrist is demanded concurrently with ulnar deviation. Since tool-wrist-forearm configuration is often a function of the proximity of the worker to the workbench, or the location of the chair, close attention should be paid to these extraneous potential causes of handtool imposed work stress.

Dorsiflexion of the wrist while the forearm is pronated should be avoided. This combination predisposes to radio-humeral bursitis (i.e., "tennis elbow"). To exert excessive stress on the elbow joint by this configuration, repetitive pronation and supination of the forearm need not be part of the task. Stresses on the radio-humeral joint, which may be potentially pathogenic, can be imposed also while the forearm is stabilized in pronation, such as when hammering overhead in an awkward position.

Generally speaking, tool-hand configurations which are conducive to motions like "laundry wringing," insertion of screws, looping of wires using pliers, or repetitive manipulation of switches or controls rotating coaxially with long rods, such as those found on the steering handles of motorcycles, require careful biomechanical analysis in order to avoid damage to forearm, wrist, and hand.

Many of those strong muscles which flex and extend the fingers come from the elbow region and are connected by tendons to the phalanges. Because of the peculiar construction of the tendon-tendon sheath system, a potential risk of "trigger finger" is imposed when any finger other than the thumb must be frequently flexed against resistance. This is true for both dynamic as well as isometric flexion. The level of exposure is increased when a tool handle is so large that the distal phalanx must be flexed before the more proximal phalanges can be flexed and prepositioned (Figure 32-37). "Trigger Finger" is the vernacular term for two different conditions, both having the same effect. Either overwork may result in the impression of a groove on the tendon where it enters a guiding tunnel in the hand, or alternatively a nodule may arise on sheath or tendon and lock the mechanism when it is squeezed within the sheath.

In either case, the flexor muscles are able to flex the finger against the resistance of the trigger mechanism, but the extensors are too weak to straighten it out after locking. The finger must then be extended by external manipulation and this extension is usually accompanied by a small click caused by the sudden release of a groove or nodule.

All trigger-controlled hand or power tools should be subject to careful biomechanical analysis. Often triggers can be replaced by pushbuttons which can be operated easily by the thumb. Unlike the other fingers, the thumb is flexed, abducted and opposed by strong short muscles located within the palm of the hand. It can therefore actuate pushbuttons and triggers repeatedly and strongly without fatigue.

The handles of rotating tools should be positioned at an angle of roughly 120° with the longitudinal axis of the tool. This angle is desirable because the axis of rotation of the forearm runs from the lateral side of the elbow through a point located roughly at the base of the ring finger (Figure 32-38). However, the optimal axis for transmission of thrust runs from the base of the index finger through the center of the capitulum of the humerus. It runs parallel with the longitudinal axis of the forearm and at an angle of approximately 10° with the axis of rotation, while the "axis of grip" of the closed fist runs at an

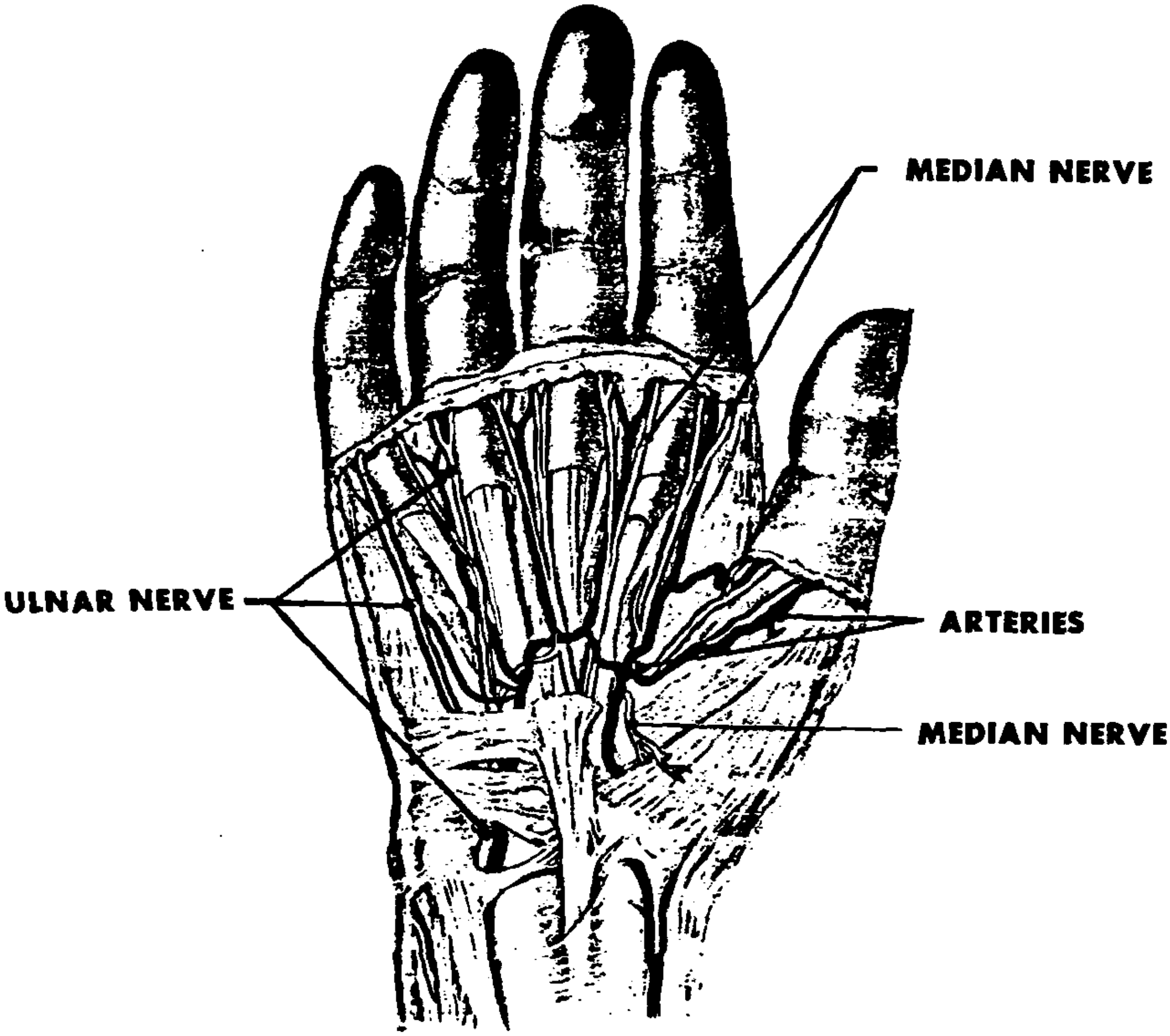


Figure 32-33. Position of the Most Important Arteries and Nerves in the Palm of the Hand.

angle of 70° with respect to the best line of thrust transmittal.

If thrust is required for the effective operation of a tool, then the implement should be designed so that this force vector is directed towards the base of the thumb and the broad distal end of the radius (Figure 32-38). Thrust should never be applied so that it acts against the heel of the little finger because this would produce a bending moment on the wrist which could cause fatigue, discomfort and, in extreme cases, trauma to nerves, tendons or blood vessels.

It is often possible to design a rotating tool so that its tip emerges from the hand between the middle and the ring finger, or if thrust is required, between the index and the middle finger. This, in spite of its occasionally awkward appearance, produces excellent results from the point of view of working comfort and endurance.

Optimal musculo-skeletal configuration of the forearm may frequently be achieved by bending the tool instead of flexing the wrist.

### Materials and Weights for Tools and Handles

Tool weight should be determined according to the nature of the task to be performed. A tool housing vibrating components, especially pneumatic and power tools, should be sufficiently heavy to possess inertia adequate to prevent transmission of excessive vibration onto the human body. If this requires excessive weight, then recourse should be taken to suspension mechanisms and counterweights. The center of mass of heavy tools should be located as close as possible to the body of the operator in working posture and preferably on a transverse plane passing through the umbilicus (Figure 32-39). Materials for tool handles to be operated by the ungloved hand should be poor conductors of heat and electricity. All handles should have a surface texture rough enough to permit secure gripping and avoid slipping in operation. Handles should be hard enough so that they will not allow chips, small components, grit or injurious materials to be imbedded. They