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Repetitive Trauma Disorders: Job Evaluation and Design

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Repetitive trauma disorders of the upper extremity are a major cause of lost work in many hand-intensive industries. Reported risk factors include repetitive and forceful exertions, certain postures, mechanical stress, low temperatures, gloves, and vibration. Risk factors can be identified with job analysis procedures based on traditional work-methods analysis. Risk factors can be controlled through reallocation of work, balancing of tools, selection of alternative tool designs, work relocation, selection of suitable hand protection, and elimination of hand exposure to low temperatures and vibration. Drawing-board manikins are used with computer-aided design systems to estimate the best work location for a given task.

INTRODUCTION

Upper-extremity repetitive trauma disorders, such as carpal tunnel syndrome and tendonitis, are a major cause of lost time and workers' compensation in many hand-intensive industries. As much as 25% of the work force in some jobs are afflicted with disorders requiring medical attention (Armstrong, Foulke, Joseph, and Goldstein, 1982; Fine, Silverstein, Armstrong, and Anderson, 1984; Hymovich and Lindholm, 1966; Jensen, Klein, and Sanderson, 1983; Silverstein, 1985; U.S. Department of Labor, Occupational Safety and Health Administration, 1977; Wehrle, 1976; Wisseman and Badger, 1977). Reported factors of occupational repetitive trauma disorders include repeated or sustained exertions, certain postures, vibration, low temperatures, and gloves. This paper describes procedures for analysis, identification of recognized risk factors, and engineering control of occupational repetitive trauma disorders. The use of computer-aided design programs for workstation design is also discussed. The examples included in this paper are hypothetical; however, they encompass elements of many real situations observed by the authors.

JOB ANALYSIS

Job analysis consists of two steps: (1) a work-methods analysis, based on traditional techniques of time-and-motion study to determine the work content of the job, and (2) a systematic analysis of risk factors (Armstrong, 1983; Armstrong et al., 1982).

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Traditional industrial engineering work-methods procedures are used to analyze the work requirements (Barnes, 1972). First, the required tasks are identified. Second, each task is described as a series of steps or elements. Elements are fundamental movements or acts required to perform a job, such as reaching, grasping, and moving. Element definitions suggested by Gilbreth and Gilbreth (1924) are listed in Table 1; Gilbreth called these elements *Therbligs* (Barnes, 1972). Although formal element definitions have been suggested, they should be considered arbitrary, and detail can be increased or decreased as necessary.

Elements are determined by observing the job on site or watching videotapes of the job played in slow motion. Tasks are defined as elements performed, usually in the same sequence, to accomplish a common end. Examples of tasks might include the following: get pallet, load pallet, clean work area, stuff circuit board, and sand part. Tasks are determined by examining available job descriptions, talking to supervisors and workers, and observing the job as it is performed. The time required to perform each task can be determined using available time-study or production records, or it can be measured directly with a stopwatch. After the work content has been determined, the next step is to review each element for recognized occupational risk factors of repetitive trauma disorders.

TABLE 1

Work Elements or "Therbligs" Suggested by Gilbreth (1924) and Modified by Barnes (1972)

Search	Select
Grasp	Reach
Move	Hold
Position	Inspect
Assemble	Disassemble
Use	Idle
Unavoidable Delay	Avoidable Delay
Plan	Rest to Overcome Fatigue

A job entitled *attach brackets*, shown in Figure 1, is typical of many manual-assembly jobs. It consists of the following steps: get seat cushion from stack and position it on bench; get screws from bin and screwgun from bench, and position screw in nut runner; get bracket and position on cushion; drive three screws to attach bracket; repeat for second bracket; set screwgun aside on bench; and push cushion with bracket onto a conveyor. It can be summarized into the following task analysis:

(1) REACH, GRASP, MOVE, POSITION cushion from stack
(2) REACH, GRASP, MOVE screwgun
(3) REACH, GRASP, MOVE four screws from bin
(4) MOVE, POSITION one screw in screwgun
(5) REACH, GRASP, MOVE, POSITION bracket on case
(6) MOVE, POSITION, USE screwgun to attach bracket
(7) MOVE screwdriver away from bracket ⎫
(8) MOVE, POSITION, screw in screwgun ⎬ 3 times
(9) MOVE, POSITION, USE screwgun to attach bracket ⎭
(10) MOVE screwgun to bench
(11) REACH, GRASP, MOVE cushion-bracket to stack

Observe that certain sequences of elements are often repeated. Sequences such as REACH–GRASP–MOVE and MOVE–POSITION–RELEASE are simplified using the terms GET and PUT. Substitution of terms simplifies the above task analysis to:

(1) GET cushion from stack
(2) PUT cushion on work bench
(3) GET screwdriver from bench
(4) GET screw
(5) PUT screw into screwgun
(6) GET bracket
(7) PUT bracket on cushion
(8) PUT screw in bracket
(9) PUT screw into screwgun ⎫ 3 times
(10) PUT screw into bracket ⎭
(11) PUT screwgun on bench
(12) GET cushion-bracket
(13) PUT cushion-bracket on conveyor

Other simplifications can be developed as

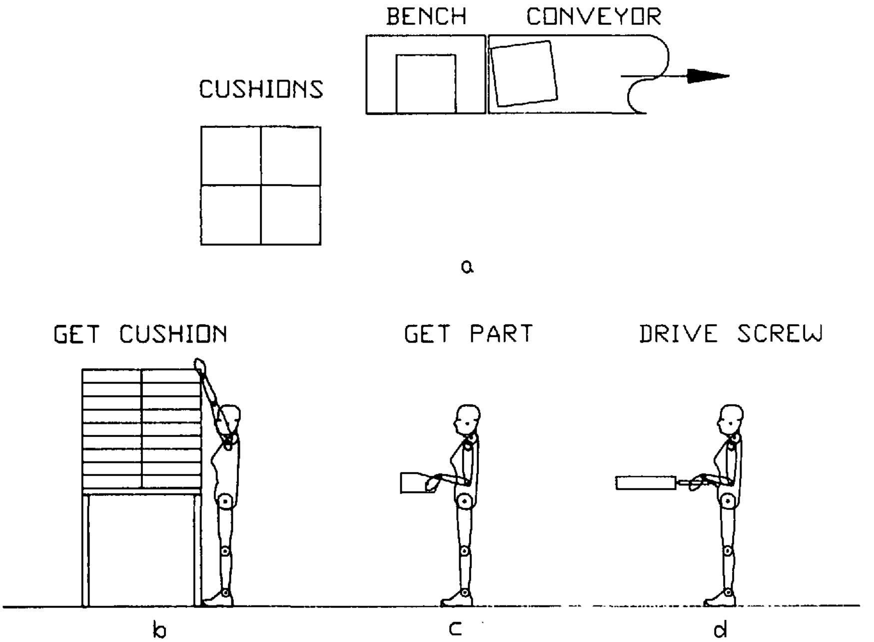

Figure 1. *Workstation layout for attaching bracket to cushion is shown in a. The worker gets a cushion, b, gets bracket and screw, c, drives screw, d, and puts cushion and bracket assembly on the conveyor, a.*

necessary. In many cases, engineering work-methods analyses are performed as part of the company's effort to develop work standards, and additional analysis to determine work content is not required. After all of the work requirements have been determined for the job, the next step is to review each element for the presence of recognized risk factors of repetitive trauma disorders.

IDENTIFICATION OF RISK FACTORS

Most studies of repetitive trauma disorders have focused on either diagnosis or treatment. Within these studies are numerous references demonstrating that occupational risk factors can cause, precipitate, or aggravate these disorders. These factors, including repetitive and sustained exertions, certain postures, vibration, low temperatures, and mechanical stresses, and the references in which they are cited, are summarized in Table 2. Although these factors frequently are cited as causes of repetitive trauma disorders, acceptable exposure levels to individual and combined factors have not yet been determined. The presence of a factor does not necessarily mean that the person doing the job is at excessive risk of injury and that job changes are worth their cost. When the presence of risk factors is combined with a history of repetitive trauma disorders among persons doing that job, the risk of injury may be excessively high and job changes may be worth their cost. In many cases, it is desirable to make changes regardless of the history because job changes are inexpensive and injuries are often very expensive. This is particularly true when jobs are being designed and set up. Table 2 can be used as a checklist to evaluate each work element for the presence of recognized risk factors of repetitive trauma disorders.

TABLE 2

Reported Risk Factors of Repetitive Trauma Disorders

Factor	Reference
1. Repetitive exertions	Cannon, Bernacki, and Walter, 1981; Hagberg, 1982; Kelly and Jacobson, 1964; Kuorinka and Koskinen, 1979; Kurppa, Waris, and Rokkanen, 1979a; Luopajarvi, Kuorinka, Virolainen, and Holmberg, 1979; Muckart, 1964; Phalen, 1966; Simon, 1975; Sperling, 1951; Thompson, Plewes, and Shaw, 1951; Tichauer, 1976; Wilson and Wilson, 1957; Wright 1945
2. Posture:	
a. Shoulder: Elbow above mid-torso reaching down and behind	DePalma and Callery, 1954; Herberts, Kadefors, Andersson, and Petersen, 1981; Lippmann, 1944; Lord and Rosati, 1958; Nichols, 1967; Simon, 1975; Wright, 1945
b. Forearm: Inward or outward rotation with a bent wrist	Hoffmann, 1981; Kurppa, Waris, and Rokkanen, 1979b; Goldie, 1964; Tichauer, 1976
c. Wrist: Palmar flexion or full extension	Armstrong and Chaffin, 1979; Phalen, 1966; Smith, Sonstegard, and Anderson, 1977; Tanzer, 1959; Tichauer, 1976
Ulnar or radial deviation	Loomis, 1951; Muckart, 1964; Tichauer, 1976; Younghusband and Black, 1963
d. Hand: Pinching	Armstrong, 1979, 1982; Smith, Sonstegard, and Anderson, 1977; Swanson, Matev, and Groot, 1970
3. Mechanical stress concentrations:	
a. Over the base of palm	Armstrong, 1983; Kendall, 1960
b. On the palmar surface of the fingers	Quinnell, 1980; Sperling, 1951; Tichauer, 1976
c. On the sides of the fingers	Dobyns, O'Brien, Linscheid, and Farrow, 1972; Kisner, 1976; Tichauer, 1976
4. Vibration	Cannon et al., 1981; Seppalainen, 1970
5. Cold	Clark, 1961; Dusek, 1957; Fox, 1967; Lockhart and Kiess, 1971; Mackworth, 1955; Morton and Provins, 1960; Scheifer, Kok, Lewis, and Meese, 1984; Stevens, Green, and Krimsley, 1977; Williamson, Chrenko, and Hamley, 1984
6. Gloves	Hertzberg, 1955; Lyman, 1957; Sperling, 1980

The major stresses identified in the example assembly task (Figure 1) include:

(1) Reaching overhead to get cushions from stack (Figure 1b).
(2) Sharp edges on screw bin (Figures 1c and 6a).
(3) Ulnar deviation required to use the screwgun (Figures 1d and 5a).
(4) Vibration from screwgun.
(5) Forceful gripping to resist the weight of the air line and the torque of the tool (Figures 1d and 2a).
(6) Cold exhaust from the air-powered hand tool.

After the major physical stresses have been identified, the workstation can be redesigned to minimize the risk of repetitive trauma disorders.

ENGINEERING CONTROLS

As noted previously, individual and combined levels of repetitiveness, forcefulness, work postures, low temperature, and vibration that can be tolerated without excessive risk of injury are not yet known. Alterations of tools, workstation layout, and/or methods

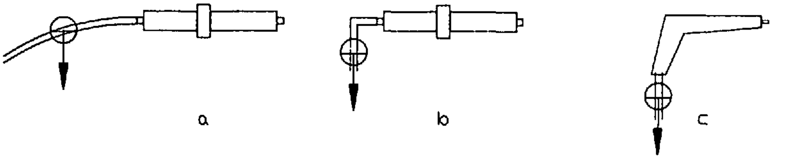

Figure 2. *Twisting of the tool out of the hand by the air line, a, can be reduced by use of a right-angle attachment, b, or by using a pistol-shaped tool, c.*

are introduced on a trial-and-error basis. In many cases, certain stresses are totally eliminated as a result of minor job changes, such as altering the location of the work or changing a tool. Data on the number of worker complaints, medical visits, and compensation claims are used to determine when the repetitive trauma disorders are under control.

Repetitive or Sustained Exertions

The repetitiveness of a job is often reduced by increasing the variety of tasks performed with a corresponding increase in work time or by rotating workers among different jobs. Care should be exercised in increasing work content to be sure that the additional tasks are compatible with the original workstation and that they do not involve the same types of work stresses as the original job. The feasibility of worker rotation often depends on the level of skill required to perform a given job as well as on labor contracts.

Force of Exertion

The force of exertion is sometimes reduced by altering the objects held in the worker's hand, for example by decreasing their weight, changing their size or shape, or balancing them. Weight is often reduced by having the worker pick up fewer objects at a time or lift with two hands rather than one.

The strength requirements of a task are reduced where the worker grasps objects with a power-grip posture rather than a pinch posture. This is because of the greater mechanical advantage which exists when the fingers are wrapped around the objects in a power grip compared with when the load is located on the end of the fingers in a pinch (Armstrong, 1982; Swanson, Matev, and Groot, 1970).

Objects should be grasped at their centers of gravity so that their weights do not twist them out of the worker's hand. When the hand location cannot be changed easily, the center of gravity can be shifted by (in order of preference) reducing, shifting, or adding weight to one side of the object. The torque caused by the air line in Figure 1c can be reduced by attaching the air line to the tool at a right angle or by using a pistol-shaped screwgun as shown in Figure 2.

Another factor in the required exertion force is the torque required to hold the tool. Torque often can be controlled using different kinds of connectors or external torque-control devices. Two torque-control devices that could be used in the examples are shown in Figure 3. Often, these devices also can be used as retractors to hold the tool when it is not in use, thus reducing the time for getting the tool and putting it away.

Posture

From Table 2, one may infer that the ideal work posture is one in which the elbow is at the side of the body, the forearm is semipronated, and the wrist is straight. As a practical matter, it is not feasible or desirable to maintain a static work posture in this position; the position does however, suffice as a

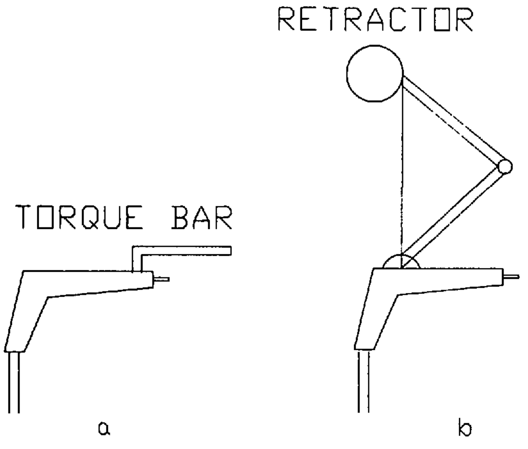

Figure 3. *Torque bars, a, and articulating retractors, b, can be used to control screwgun torque.*

starting point for workstation design. A realistic goal is a job design in which the elbows are not elevated above mid-torso height and the shoulders are neither flexed nor abducted more than 60 deg. This prevents extreme pronation and supination of the forearm as well as extreme deviation, extension, and flexion of the wrist.

Work posture can usually be controlled through the location and orientation of the work or through tool design. For example, reaching overhead for cushions can be controlled by instructing the stock person not to stack material above head height, as shown in Figure 4b. The ulnar deviation required to hold and use the screwgun is reduced by using a jig to hold the cushion at the proper location and orientation, as shown in Figure 5b. When it is not possible to relocate parts, alternative tools should be investigated. For example, the ulnar deviation required to hold the in-line design can be reduced using a pistol-shaped screwgun, as shown in Figure 5c. The effectiveness of the pistol-shaped tool in controlling a stressful work posture in this example, however, does not make it the tool of choice in all situations. For example, its use at a horizontal work surface at bench height can result in wrist flexion or ulnar deviation (see Figure 5d). The appropriateness of a tool is determined only in the context of a given application. Procedures using computer-aided drafting for estimating the proper work location and orientation and proper tool are discussed later in this paper.

Mechanical Stress Concentrations

Stress concentrations on the hand usually are controlled by increasing the size of handles, eliminating or rounding sharp edges, and using pliant materials. Handles should be as large as will fit comfortably in the hand. The feasibility of enlarged handles

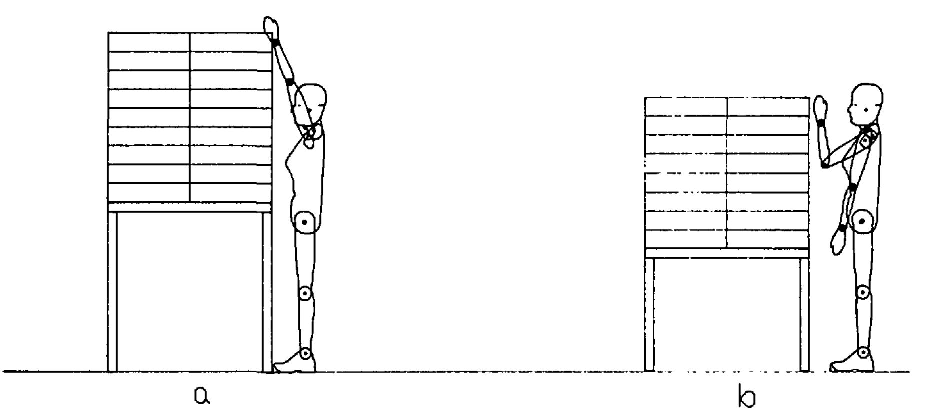

Figure 4. *Postural stress from reaching overhead for parts, a, can be controlled by lowering the parts, b.*

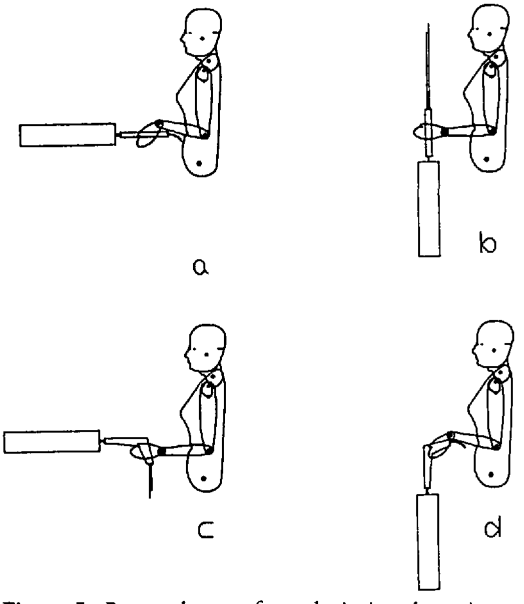

Figure 5. *Postural stress from deviating the wrist, a, to use the in-line screwgun, can be controlled by relocating the part, b, or by using a different tool design, c. Postural stress is produced in the wrist by using a pistol-shaped screwgun on a horizontal work surface, d.*

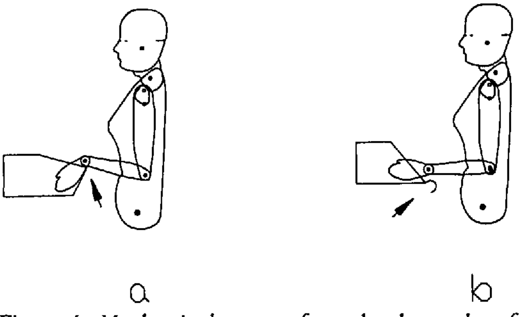

Figure 6. *Mechanical stresses from the sharp edge of the screw bin, a, can be controlled by rounding the edge, b.*

depends on the force and dexterity requirements of the task. For example, a screwdriver used to insert large wood screws could be much larger than one used for inserting screws in an electronic circuit.

Workstations should be designed so that workers need not come into contact with the hard, sharp edges of benches, containers, or fixtures. When contact cannot be avoided, the edges should have the largest possible radii of curvature. The stress concentration on the wrist when the worker gets screws from the bin can be reduced by rounding the front edge of the bin as shown in Figure 6.

Cold

The environmental air, tool exhaust, and materials that come into contact with the workers' hands should not be colder than 20°C for prolonged or repeated contact with the hand (Clark, 1961; Dusek, 1957; Fox, 1967; Lockhart and Kiess, 1971; Mackworth, 1955; Morton and Provins, 1960; Scheifer, Kok, Lewis, and Meese, 1984; Stevens, Green, and Krimsley, 1977; Williamson, Chrenko, and Hamley, 1984). Exhaust air from powered tools should be directed away from the hand. This also reduces workers' exposure to noise and possible oil mist from an air-powered tool. In some cases a second air line may be required to carry exhaust air away from the tool and the worker. Metal tool handles are highly thermally conductive and can be insulated with a thin layer of rubber or plastic. The effects of low environmental temperatures can be minimized by keeping the worker's body warm. Gloves or mittens can be used to help keep the hands warm, but suitable allowances must be made for their effect on strength and dexterity.

Gloves

Gloves are commonly used to protect the hands from environmental temperature extremes, chemical contaminants, and mechanical insult. In holding tasks, gloves may enhance friction and reduce the task strength requirements (Riley, Cochran, and Schanbacher, 1985). In tasks requiring manipulation, gloves can interfere with hand movements and can attenuate strength by 30% or more, depending on the glove material and fit (Hertzberg, 1955; Lyman, 1957; Sperling, 1980). It is very difficult to fit gloves well to the hand because of extreme anthropometric variations from person to person. It is suggested that a variety of sizes and styles be made available to workers so that they can select those that are most comfortable. No more of the hand should be protected than necessary. For example, if only palm protection is required the fingers of the gloves can be cut off. If only finger protection is required, the fingers can be wrapped with safety tape rather than being gloved.

Vibration

Although vibration control is beyond the scope of this review, it suffices to say that vibration should be minimized. Factors considered in controlling vibration exposure include frequency and magnitude of the vibration source, duration of exposure, temporal exposure patterns, forces applied by the tool operator, direction of vibration, skill of the operator, and posture of the hand, arm, and body during exposure. (See Brammer and Taylor, 1982, pp. 303-337, for other material on vibration control.)

POSTURE AND WORKSTATION LAYOUT

It has been mentioned that work posture can be controlled through the location and orientation of work and the design of tools. In many cases, this concept can be shown graphically using drawing-board manikins. A manikin representing a worker of a particular anthropometry is located in the work position (e.g., standing erect, sitting straight, kneeling, squatting) on a workplace drawing. If it is determined that the manikin's hand cannot be positioned to hold or manipulate the required controls, tools, or parts in a nonstressful posture (see stressful postures in Table 2), either the worker or the work must be relocated until a more desirable posture is obtained.

Numerous two-dimensional manikin models have been proposed for drawing-board analysis of workstations (Carlyle, 1960; Dempster, 1955; Kennedy, 1982; Roebuck, Kroemer and Thomson, 1981; Woodson, 1954). The manikin designs proposed by Kennedy (1982) for aircraft cockpit design are used here because they represent both the male and the female populations, they are well documented, and they are based on contemporary anthropometric studies. The Kennedy manikins were designed to represent a female with fifth-percentile eye height and a male with ninety-fifth-percentile eye height. The manikin plans include smallest and largest practical limb sizes for persons with these percentile eye heights; average extremities, however, have been used here. Although these manikins were designed to represent air force flight personnel, they can be used for first-order approximations of the young and physically fit working population with fifth- and ninety-fifth-percentile statures. The stature of the fifth-percentile female manikin, 152.4 cm, compares favorably with that of the 151.3 cm fifth-percentile civilian female stature reported in the National Health Survey. Similarly the stature of the ninety-fifth-percentile male manikin, 188.6 cm, closely compares with that of the 186.9 cm ninety-fifth-percentile civilian male (Kennedy, 1982; U.S. Department of Health Education and Welfare, 1979).

Although drawing-board manikins can be manipulated with standard drafting techniques on workplace and equipment drawings, they are used more easily with computer-aided drafting (CAD) systems. CAD systems provide the ability to create engineering drawings that can be stored in files and recalled for later editing or plotting. Entire manikins, or manikin parts, can be stored and recalled, scaled and superimposed onto a workplace drawing at a desired orientation. Menus are often constructed to facilitate retrieval. A number of commercially available CAD systems can now be operated on microcomputers. Relatively low software cost and widespread microcomputer availability make it possible to utilize drawing-board manikins in workstation design on a routine basis. Applications using microcomputer-based systems can be easily adapted to more sophisticated mainframe systems.

The most desirable workstation layout for minimizing the risk of a repetitive trauma disorder is one in which the task can be performed with the elbow at the side of the body, without excessive forearm rotation, and without the worker deviating, flexing, or fully extending the wrist. Consequently, when working on a vertical surface with a pistol-shaped screwgun the forearm should be horizontal. Representations of this posture for persons with fifth-percentile-female and ninety-fifth-percentile-male statures and average proportions are shown in Figure 7. Using a sagittal-plane manikin, the work location that accomplishes this varies from 100.1 cm for the small female to 121.2 cm for the large male.

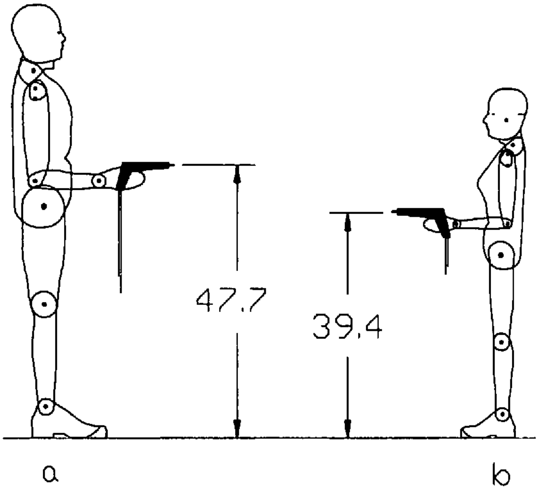

Figure 7. *Estimated postures required to hold and use pistol-shaped screwguns against vertical surface from two-dimensional representations of persons with ninety-fifth-percentile-male and fifth-percentile-female statures.*

In addition to their use in determining work locations and orientations for specific tasks, drawing-board manikins can be used to estimate ranges of reach limits for various postural constraints. The maximum reach limits in the plane of the shoulder can be estimated by rotating the arm, forearm, and hand about the shoulder as shown in Figure 8. This is not a simple rotation because the shoulder girdle shifts in the direction of the reach, thus increasing the reach by a much as 7.0 cm vertically and 5.6 cm horizontally for the fifth-percentile female, and 9.2 cm vertically and 7.8 cm horizontally for the ninety-fifth-percentile male. The arm of the manikin must be translated as well as rotated. The reach limits should be reduced by one-half the hand length if grasping is required. As summarized in Table 2, reaching overhead can lead to shoulder problems. Acceptable overhead reach limits for repetitive reaching can be estimated by constraining the shoulder to 60 deg of forward flexion, as shown in Figure 8. Other constraints can be introduced from Table 2 as necessary.

It is important to emphasize that drawing-board manikin are two-dimensional approximations of a three-dimensional system. Professional judgment, mock-ups, and prototypes should be used to evaluate results based on two-dimensional analyses. Errors can be minimized by limiting the application of manikins to situations in which the worker can face the work and is not attaining the limits of the reach envelope. Most users will find these errors acceptable, and certainly more tolerable, than the complexity and ex-

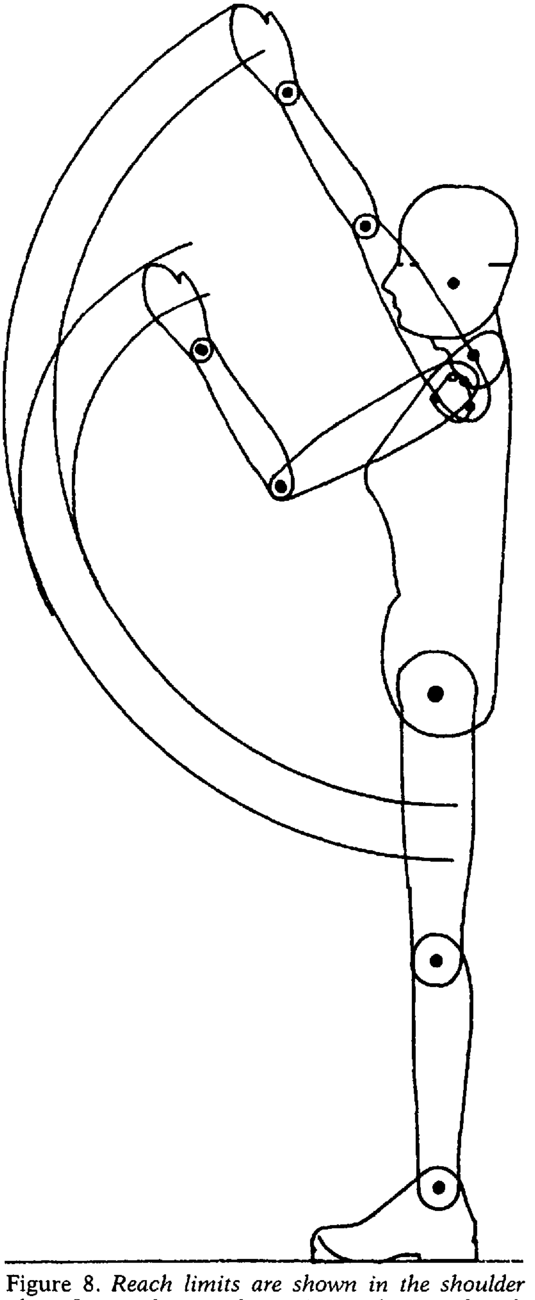

Figure 8. *Reach limits are shown in the shoulder plane for touching and gripping without and with forward shoulder flexion restricted to 60 deg.*

pense of three-dimensional dummies and computer simulations.

SUMMARY

Repetitive trauma disorders of the upper extremities are a major cause of lost work in many hand-intensive industries. Reported risk factors include repetitive and forceful exertions, certain postures, mechanical stress, low temperatures, gloves, and vibration. Risk factors are identified using job analysis procedures based on traditional work-methods analysis. Risk factors can be controlled through reallocation of work, balancing of tools, selection of alternative tool designs, relocation of work, selection of suitable hand protection, and elimination of hand exposure to low temperatures and vibration. Drawing-board manikins can be used with computer-aided design systems to estimate the best work location for a given task.

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