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Musculoskeletal Overexertion Injuries in the United States: Mitigating the Problem Through Ergonomics and Engineering Interventions

Anil Mital[1] and Arunkumar Pennathur[1]

Rehabilitating and accommodating injured workers when they return to work is a contemporary issue that is being addressed by rehabilitation experts in a variety of ways. Even though the Americans with Disabilities Act (ADA) and the Occupational Safety and Health Administration (OSHA) are mandating that employers provide reasonable accommodation to returning workers, it is the need to control increasing workers' compensation costs that is forcing employers to rethink their injury management strategies. Historically, the preventive approach has been advocated by ergonomists in the belief that all injuries can be prevented. However, available injury data from different sources, such as the National Safety Council and the Bureau of Labor Statistics presented in the initial sections of this paper, show that both the incidence and costs of occupational injuries in the United States continue to rise. It is clear, that no matter what preventive measures are taken, some injuries will happen. With this in mind, this paper examines the current injury management approach, and suggests an integrated injury management model incorporating the principles of ergonomics and engineering design, and the principles of disability management. Further, this paper highlights ergonomics interventions that industries should follow for injury management. The paper also provides guidelines and recommendations from ergonomics research for identification, quantification, and control of risk factors associated with musculoskeletal injuries of the back and the upper extremities.

KEY WORDS: injury management; rehabilitation of injured worker; ergonomic interventions; musculoskeletal injury risk factors.

INTRODUCTION

Work-related injuries are a major concern to industries, academic researchers, and public and government agencies. Industries are interested in reducing their worker compensation costs, medical payments, and costs resulting from lost work time. Besides costs, the adverse public image resulting from hazardous workplaces and work practices is another reason for industries to undertake efforts to prevent and control injuries. Health and safety researchers and practitioners are continuing efforts to prevent workplace injuries by trying

[1]Ergonomics and Engineering Controls Research Laboratory, University of Cincinnati, Cincinnati, OH 45221-0116; e-mail: amital@uceng.uc.edu.

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to understand the causal mechanisms underlying workplace injuries, and by designing safer workplaces through job, equipment and workplace design, and employee education. In the process, researchers are beginning to question the wisdom of having a "zero-injuries" goal. While this realization is resulting in novel injury management methods, such as the integration of disability management techniques with ergonomics and engineering design (1–3), technological changes in industries resulting from what has been called the "information technology revolution," and the resultant effects on health and safety of the industrial worker (incidences of carpal tunnel syndrome, for example), however, are adding to the woes of researchers. Technology is not only causing new health and safety problems to manage, but has also been ineffective and counterproductive in solving existing problems (the case of automation is an example—designers have been able to automate only simple tasks, leaving the difficult ones for humans to perform). Available nonfatal occupational injury data and observed trends in such data, indicate that, in the U.S., injuries to the back and the upper extremities continue to be prevalent and expensive to manage.

The goal of this article is to critically examine and redefine the role of ergonomics in injury management and rehabilitation of the injured worker. First, we briefly present the different injury management approaches and elements of an integrated injury management model. Next, we focus on the role of ergonomics in mitigating/reducing musculoskeletal injuries.

MEASURES OF THE MAGNITUDE OF THE OCCUPATIONAL INJURY PROBLEM

Traditional measures of the prevalence and magnitude of injuries include the number of injuries, incidence rates for different industries, injury costs, and lost work time. In the following subsections, data pertaining to these overall measures for U.S. industries are presented.

Number and Incidence Rates of Injuries

The National Safety Council (NSC) (4) estimates that there were 3,900,000 work-related injuries in the U.S. in 1996 alone. This number is more than double the number of injuries NSC reported in 1984 (Fig. 1).

Figure 2 provides the NSC incidence rates for all industries in the U.S. for work-related accidents. These incidence rates are computed per 1,000,000 hours of exposure, and by place of accident (workplace, in this case). These rates decreased from 1985 to 1991, but then more than doubled between 1991 (6.8) to 1996 (14.2). The Bureau of Labor Statistics (BLS) (5) publishes incidence rates for different industry divisions in the U.S. The BLS incidence rates are based on the following computation:

$$\text{Incidence rate} = \frac{(\text{No. of Injuries \& Illnesses } *200{,}000) \text{ OR } (\text{No. of lost workdays } *200{,}000)}{\text{Total hours worked by all employees during period covered}}$$

where 200,000 is the base for 100 full-time workers, working 40 hours a week for 50 weeks per year. The BLS data include incidence rates for three exclusive categories of injuries

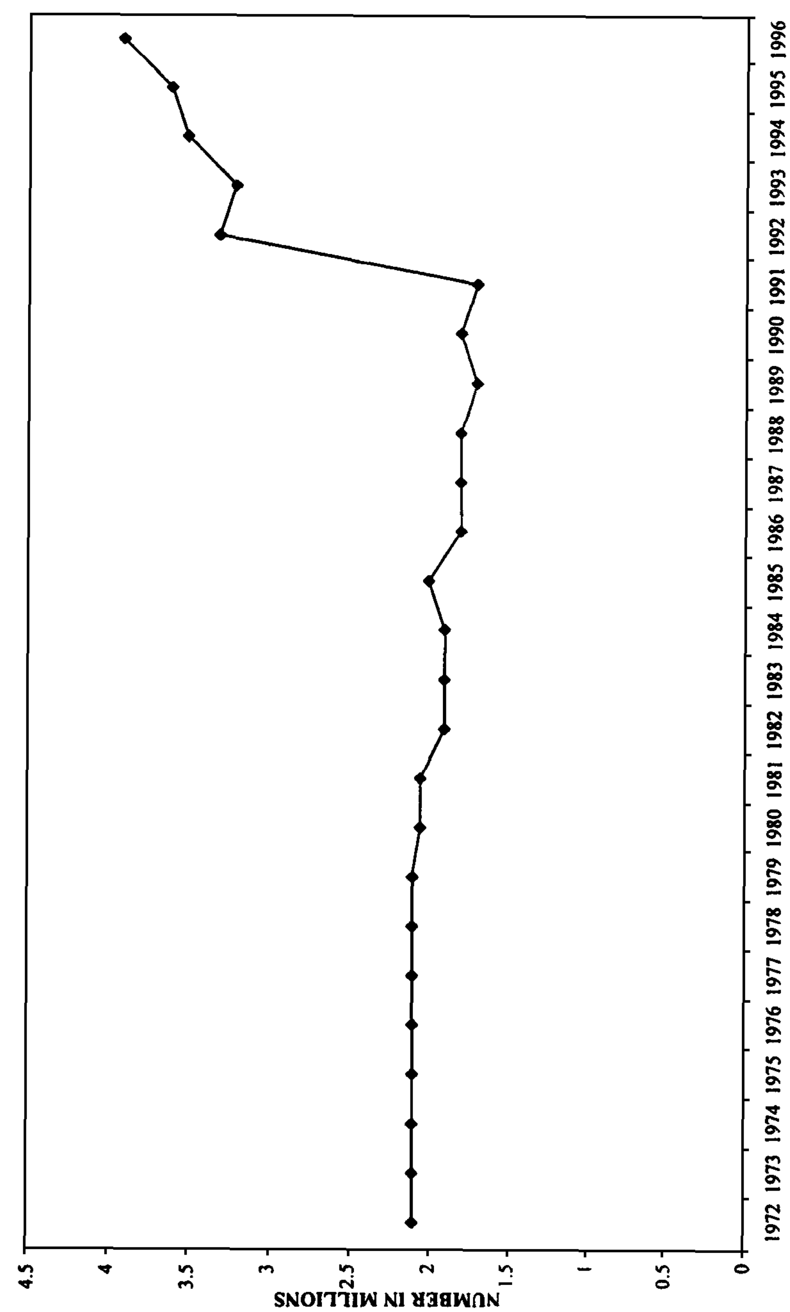

Fig. 1. Total number of injuries in the United States (Source: National Safety Council).

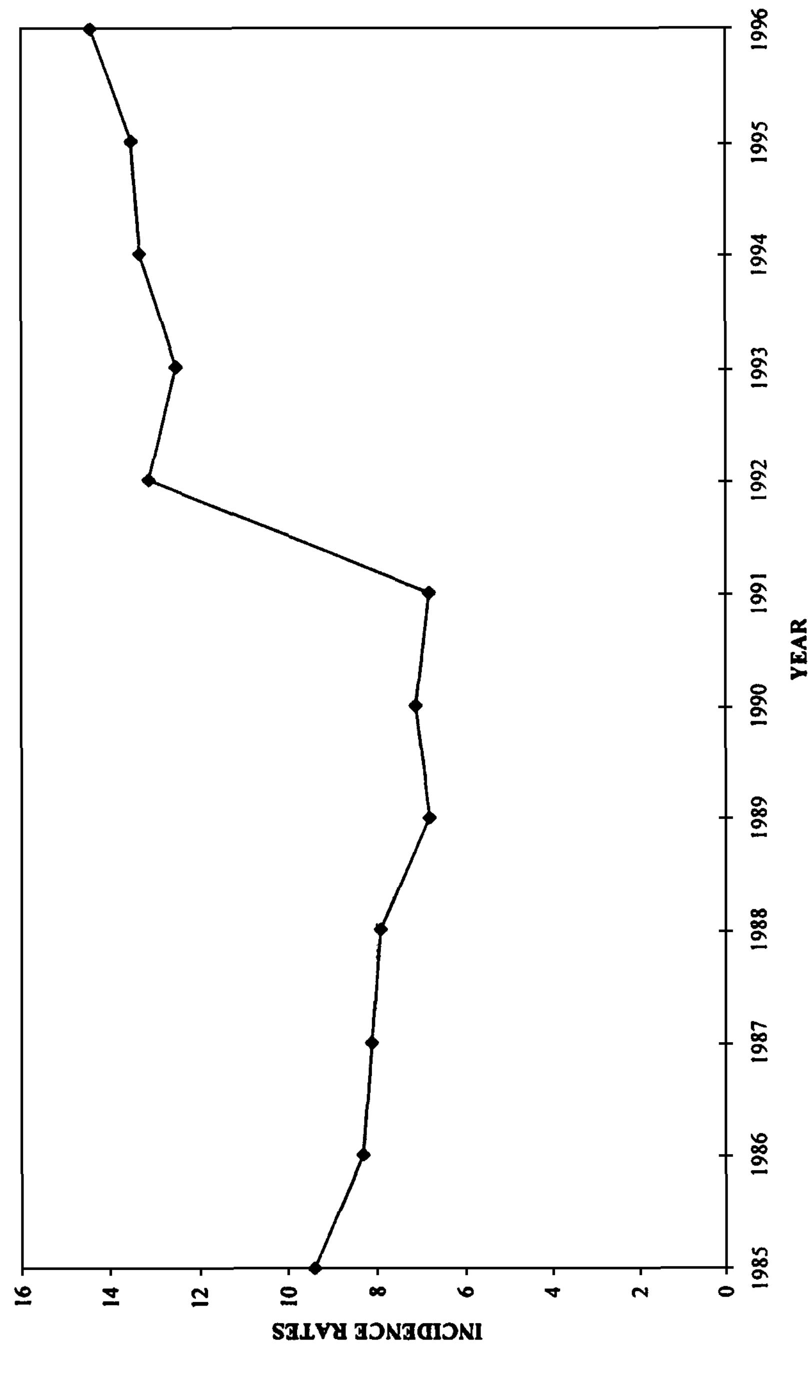

Fig. 2. National Safety Council incidence rates for all U.S. private industry.

and illnesses:

1. all recordable cases (includes fatal and nonfatal cases),
2. lost workday cases in which a worker would have worked but could not because of occupational injury or illness, and
3. nonfatal cases without lost workdays (does not involve fatalities or lost workdays):
   a. transfer to another job or termination of employment, or
   b. medical treatment other than first aid, or
   c. diagnosis of occupational illness, or
   d. loss of consciousness, or
   e. restriction of work or motion.

Figure 3 presents the BLS incidence rates for broad US industry divisions from 1984 to 1996 for all recorded cases. Construction industry had the highest incidence rates until 1993, possibly because of fatal falls from elevated heights. In 1996, construction, manufacturing, and transportation all had the highest incidence rates for lost workday cases (Fig. 4) and manufacturing had the highest incidence of nonfatal cases without lost workdays (Fig. 5).

Injury Costs

The cost of injuries in the workplace has been increasing steadily. According to NSC estimates (Fig. 6), the total cost of workplace injuries has increased nearly ten times from what it was in 1972, to nearly $121 billion in 1996. This cost includes wage losses resulting from injuries; medical costs; uninsured costs, such as the money value of time lost by workers other than those with disabling injuries; the costs of time required to investigate accidents, write accident reports, etc.; and costs due to fire losses, excluding other property damage costs. These costs are much greater than the workers' compensation insurance alone. Review of recent BLS estimates of the total compensation paid to workers in different industries and occupational categories, and as well as the workers' compensation paid as a proportion of the total compensation, reveals interesting facts. For all workers in private industry, for a total wage of $17.97 in 1997 employers spent on the average $0.39 as worker compensation. This is nearly 2.2% of the total wages. Employer payments towards workers' compensation benefits was second only to social security, among all the benefits employers were legally required to provide their employees. Similarly, for different occupational categories in the private industry, the proportion of the total compensation paid as worker compensation is the highest for blue-collar workers followed by service workers. This questions the assertion that automation has resulted in less demanding jobs for blue-collar workers. Also, even though the total compensation for service workers in private industry was only half that of the total compensation for blue-collar workers in the private industry, both categories had nearly equal workers' compensation, generally indicating the high risk and severity of work-related injuries in the service industry. Also, the average workers' compensation costs in the mid- to late-1990s (1994 to 1997) show an increase from the early 1990s (1990 to 1993).

According to NSC estimates, injuries to the back had the highest percentages in the number of cases reported (about 25%), the highest percentages of total compensation reported (nearly 31%), and the highest number of medical and indemnity payments cases reported to the State Labor Departments during the late 1980s and the 1990s.

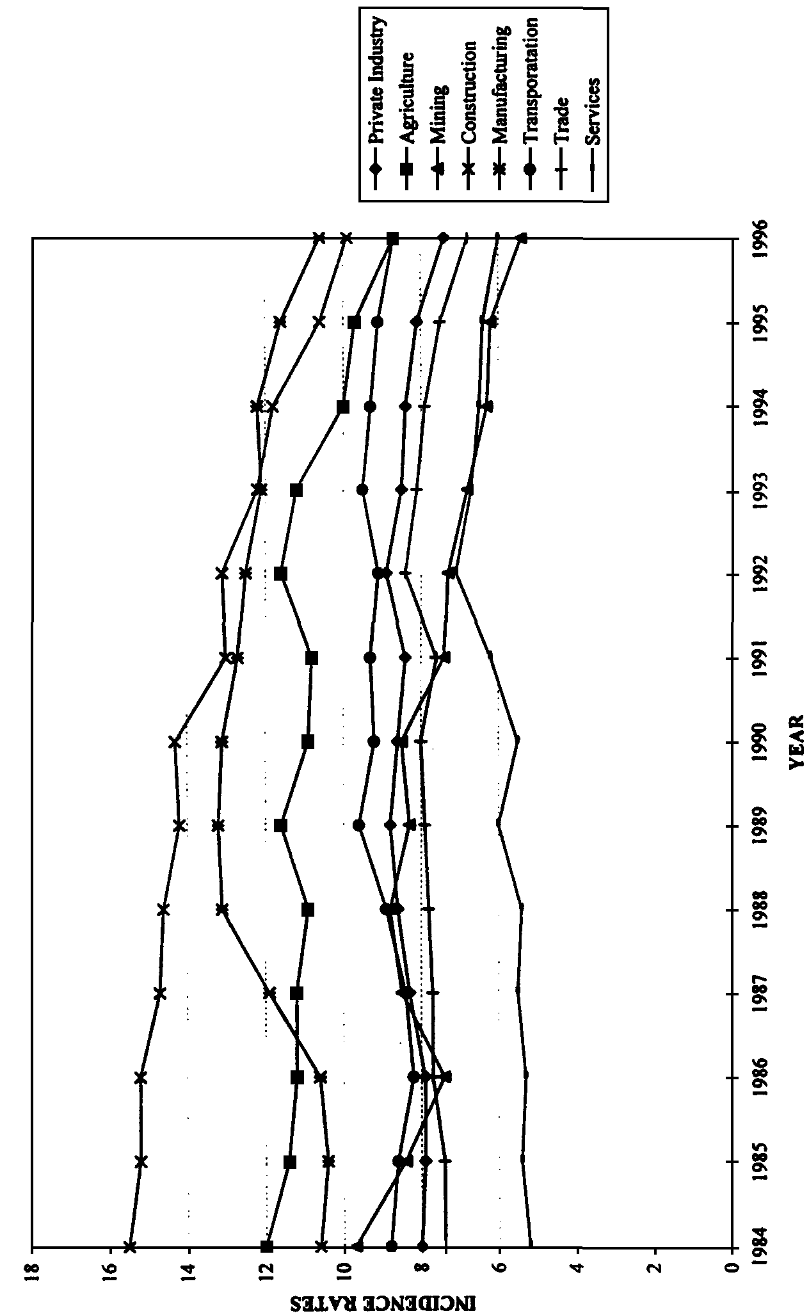

Fig. 3. Bureau of Labor Statistics' incidence rates for major U.S. industries.

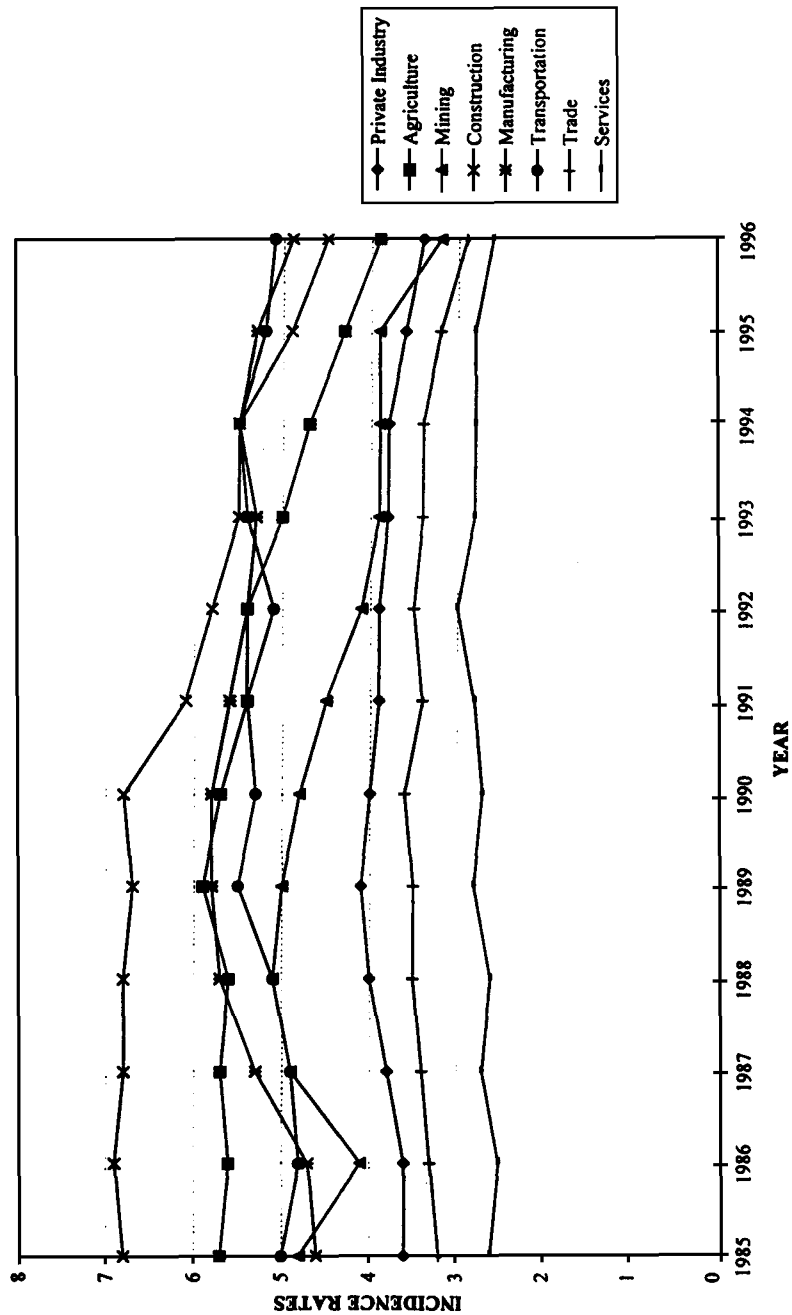

Fig. 4. Bureau of Labor Statistics' incidence rates for lost workday cases in major U.S. industries.

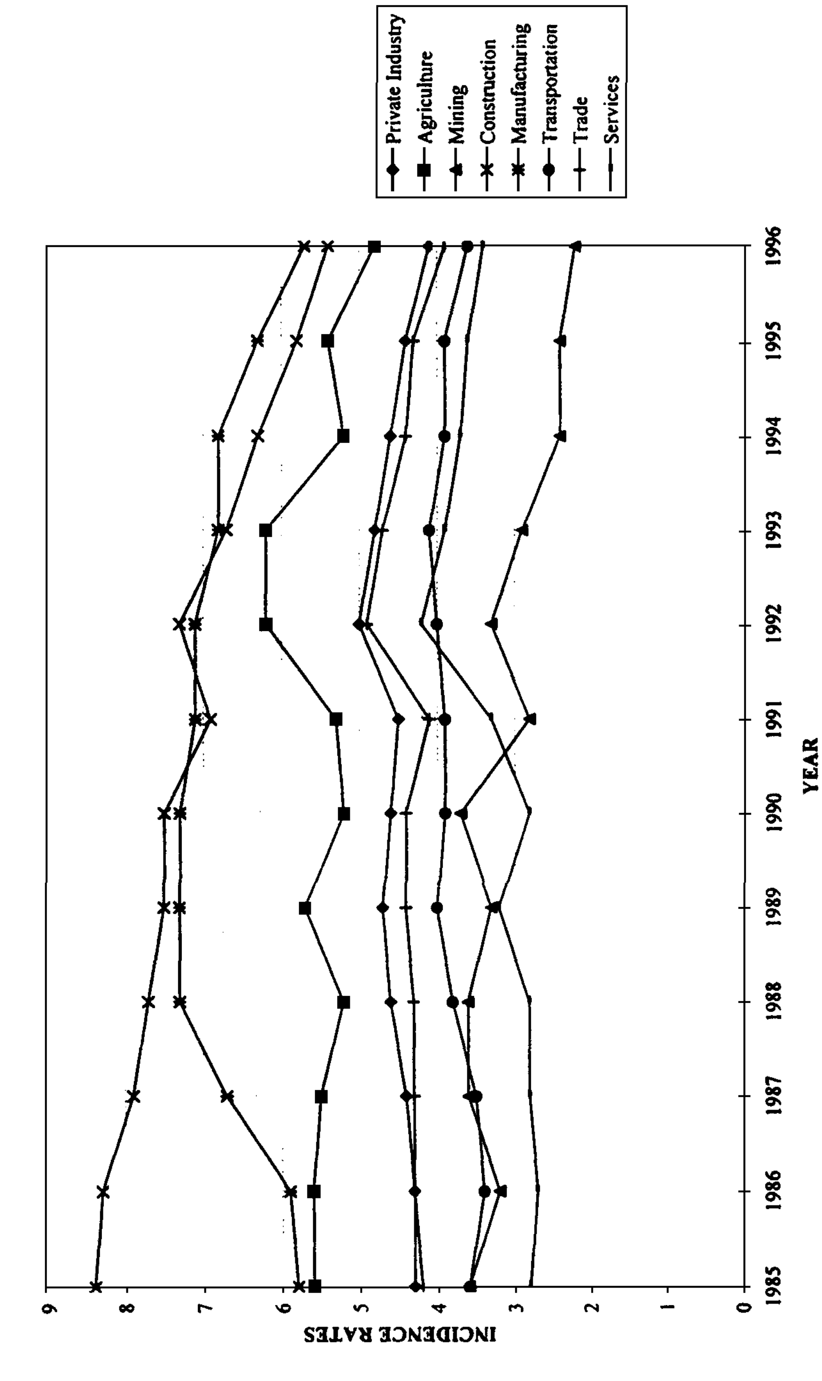

Fig. 5. Bureau of Labor Statistics' incidence rates for nonfatal cases without lost workdays in major U.S. industries.

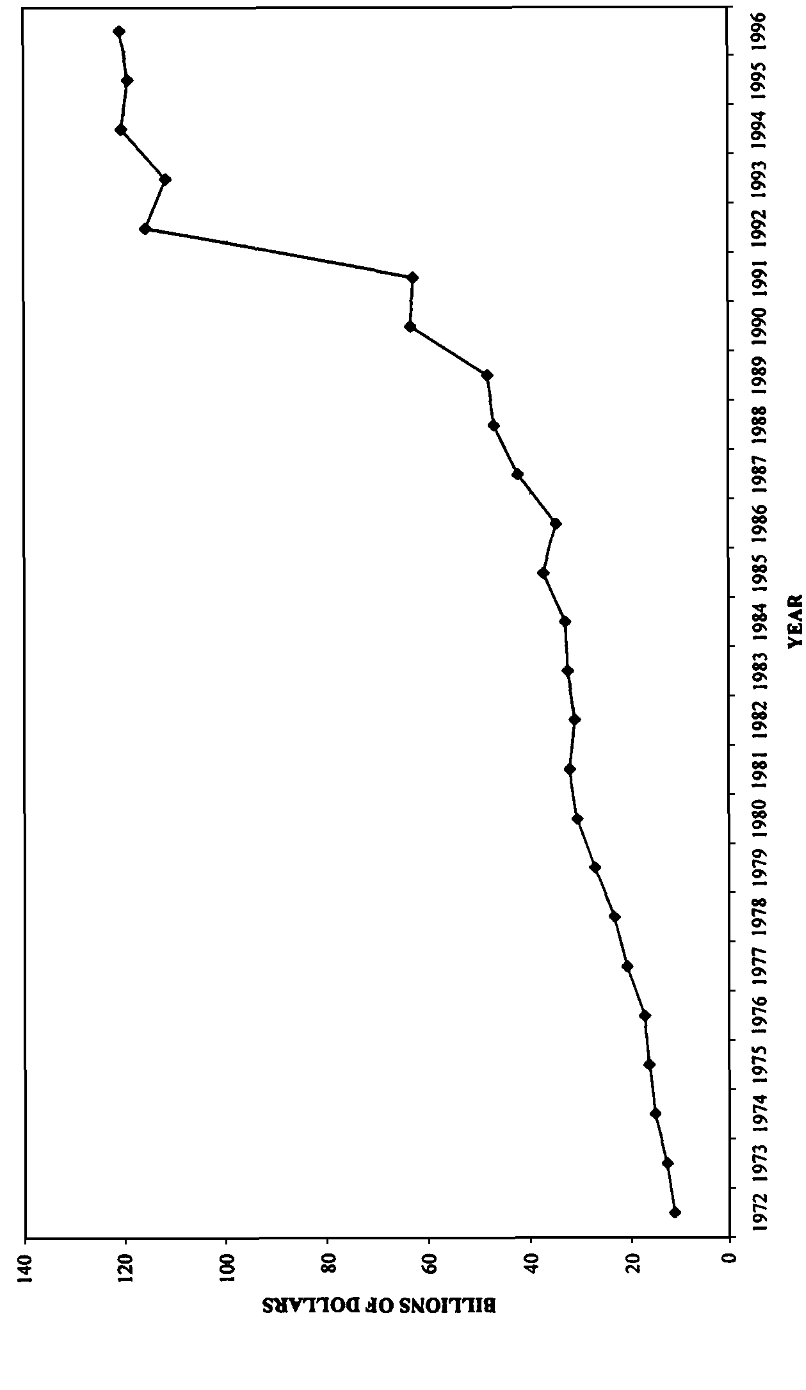

Fig. 6. Total cost of work injuries in the U.S. (Source: National Safety Council).

Fig. 7. Lost time due to work injuries in the U.S. (Source: National Safety Council).

Lost Worktime

NSC estimates that in 1996 the total worktime lost because of work-related injuries for all industries was 125 million days, an increase of 5 million days over the 1995 estimates (Fig. 7).

According to the BLS, in 1995, nearly 24% of cases with injuries to the back resulted in 3 to 5 workday losses, and nearly 18% resulted in workday losses of 31 days or more. Only about 13% of injuries to the back resulted in one workday loss. More than 30% of the injuries to the wrist in 1995 resulted in workday losses of 31 days or more. Only about 10% resulted in return to work in a day. Other than the two above-mentioned categories, injuries to most other body parts did not result in high workday losses.

Other Statistics and Trends

Truck drivers, nursing aides and orderlies, janitors and cleaners, laborers in the construction industry, assemblers, carpenters, registered nurses, and packaging machine operators are some of the occupational groups identified by BLS as high-risk occupations. The BLS summaries show that while truck driving and carpentry resulted in 31 days or more in lost workdays, most of the other occupations resulted in less workday losses. Most of the affected population in all the industries are either in the 25 to 34 age group or the 35 to 44 age group. Older workers took longer to recover from work-related injuries.

According to BLS estimates, in 1995, over 66% of the men in the private industry reported injuries resulting in workday losses and disability; and only 34% of the women reported work injuries. For all the predominantly male occupations such as agriculture, mining, construction, manufacturing, transportation and public utilities, and wholesale trade, men reported a higher number and percentage of injuries among all the injury cases reported. Women, in general, suffered a higher percentage of injuries in the service and finance industries in the 1990s. On an average, men took longer to recover from work-related injuries than women.

Figure 8 shows the proportion of injuries by part of body injured in work-related injuries. The data presented in Fig. 8 are a ratio of the total number of injuries to a certain body part in a certain year to the total number of injuries that year. Both these numbers used in the derivation of the ratio are NSC estimates. Clearly, from the standpoint of injury magnitude by body parts, injuries to the back emerge as the most important category. Overall, for all private industries, nearly 38% of the injuries were injuries to the trunk, and 27% of the injuries were injuries to the back. Injuries to the back were the highest category of injuries in the service occupations (about 31%). In all the other industries at least 23% injuries were back injuries. Upper extremity injuries, including injuries to the wrist, the hand, and the fingers, were the next highest category of injuries (23%). Manufacturing had the highest reports of injuries to the upper extremities (about 30%).

From the data presented in the above sections, it is readily apparent that injuries to the back and the upper extremities are the major categories of occupational injuries in the United States.

INJURY MANAGEMENT APPROACHES

Current approaches to management of injuries in the workplace and rehabilitation of the injured worker have been based on either ergonomics, which aims at preventing injuries in the workplace, or disability management interventions, which attempt to minimize loss time. Despite decades of ergonomics interventions, the number, severity, and cost of industrial injuries continue to be significant. Ergonomists now admit that only two-thirds of the injuries can be prevented by job design (6). Further, no amount of prevention or capital investment in prevention can achieve a zero-injury outcome.

The disability management approach, on the other hand, presumes a compensable injury and aims at minimizing the associated loss time. The focus is only on the injured worker. In trying to accommodate the person injured, disability managers ignore the needs, capabilities, and requirements of the majority. Part of the problem with injury management practiced solely on the basis of disability management principles is the training and background of disability managers. Most disability managers have no formal training in ergonomics or in design. The attempt then is to accommodate workers solely on the basis of physical limitations regardless of whether they are temporary or permanent and on transferrable work skills. Very little or no systematic attention is paid to assessing residual capacity of the injured worker; to enhancing this capacity through physical training; to assessing the effect of this physical training by measuring changes in capabilities, work, or workplace design; and determining what impact their recommendations will have on the rest of the working population, etc. All these activities are essential in successfully returning the injured worker to the same job, or for making an optimal job assignment, and ensuring that

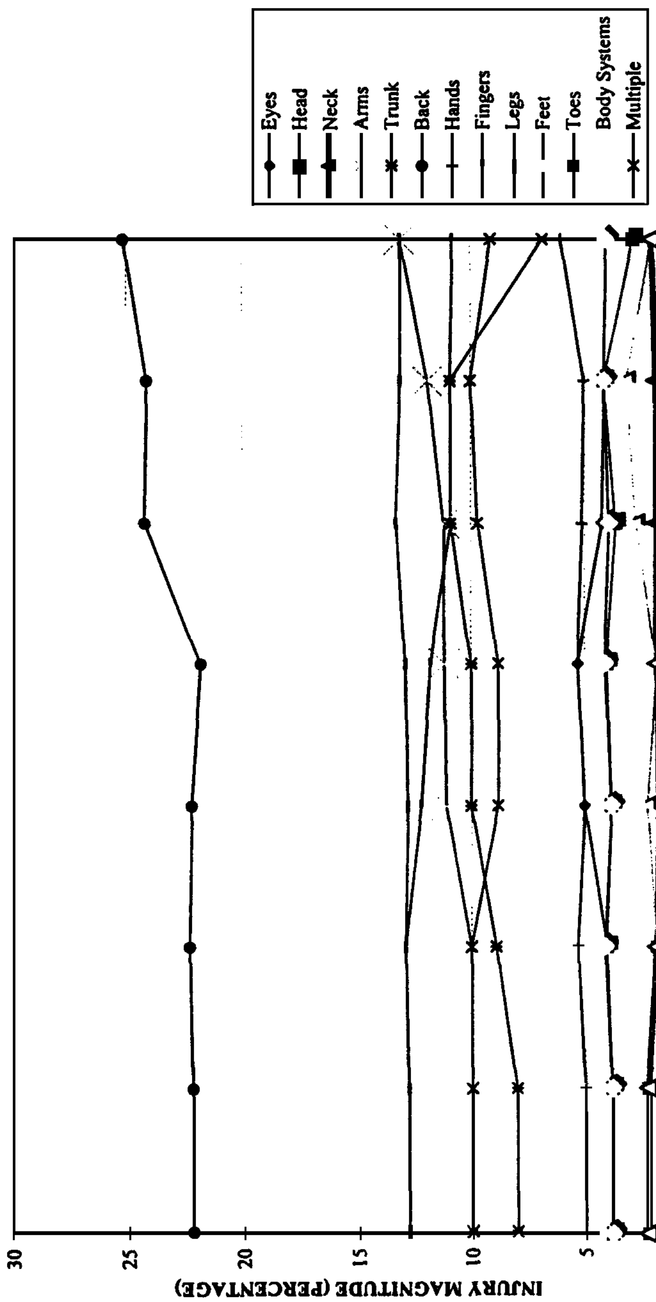

Fig. 8. Proportion of injuries by part of body injured (Source: National Safety Council).

no accommodation problems arise for other workers. Disability managers need to realize that these activities are a part of sound ergonomics analyses, and that mere "management" of the injured will not suffice in successfully rehabilitating the injured worker back to work. The next section presents an integrated (integration of disability management principles and ergonomics) injury management model.

An Integrated Injury Management Model

The two key disciplines involved in the proposed integrated injury management model are ergonomics and disability management. Figure 9 illustrates the model. The ergonomics module in the model incorporates specific design tools used for designing the work and the workplace, keeping in mind the limitations and capabilities of the worker. The overall tools involved in work design include job analysis and provision for adaptive aids. Training in ergonomics principles, assessment of physical work capacity of the workers, injury analysis, and residual capacity analysis, all have an important role to play in obtaining a good fit of the worker to the work and workplace. Design and redesign of work, workplace risk analysis, and injury analysis and cost audits play an important role in determining the suitability of the workplace to the worker. It should be noted that ergonomics and engineering interventions are only two of the many disciplines involved in disability management (see Fig. 9). Our further focus in this paper is on ergonomic engineering interventions.

ERGONOMIC ENGINEERING INTERVENTIONS FOR INJURY MANAGEMENT

The process of making a workplace ergonomically sound includes key activities such as identifying the focus areas for ergonomic intervention efforts; identifying ergonomic risk factors associated with the task, operator, machine and environment for the identified focus areas; quantifying the identified risk factors; comparing the quantified risk factors with acceptable values from ergonomics knowledge-base; and designing/redesigning task, operator, machine and environmental variables to control and reduce workplace injuries.

Determining the Focus of Ergonomic Interventions

Given that investment in ergonomics efforts is not always a top priority, or even *a* priority, in the face of other competing activities (that often dictate the bottom-line) for available resources, it is essential to focus ergonomics efforts on a few specific areas that need urgent attention. Such focus areas for ergonomic intervention efforts can be determined by reviewing employee complaints or analyzing injury data, if such data are available. A thorough review of the records, and if possible, the associated costs, will provide a good indication of areas needing attention. Identified focus areas can be further classified into areas needing immediate attention, areas that will need attention in the short term, and areas that will need attention in the long term. From the injury and cost data, incidence rates (number of cases per 200,000 work hours or per 100 workers) should be calculated for

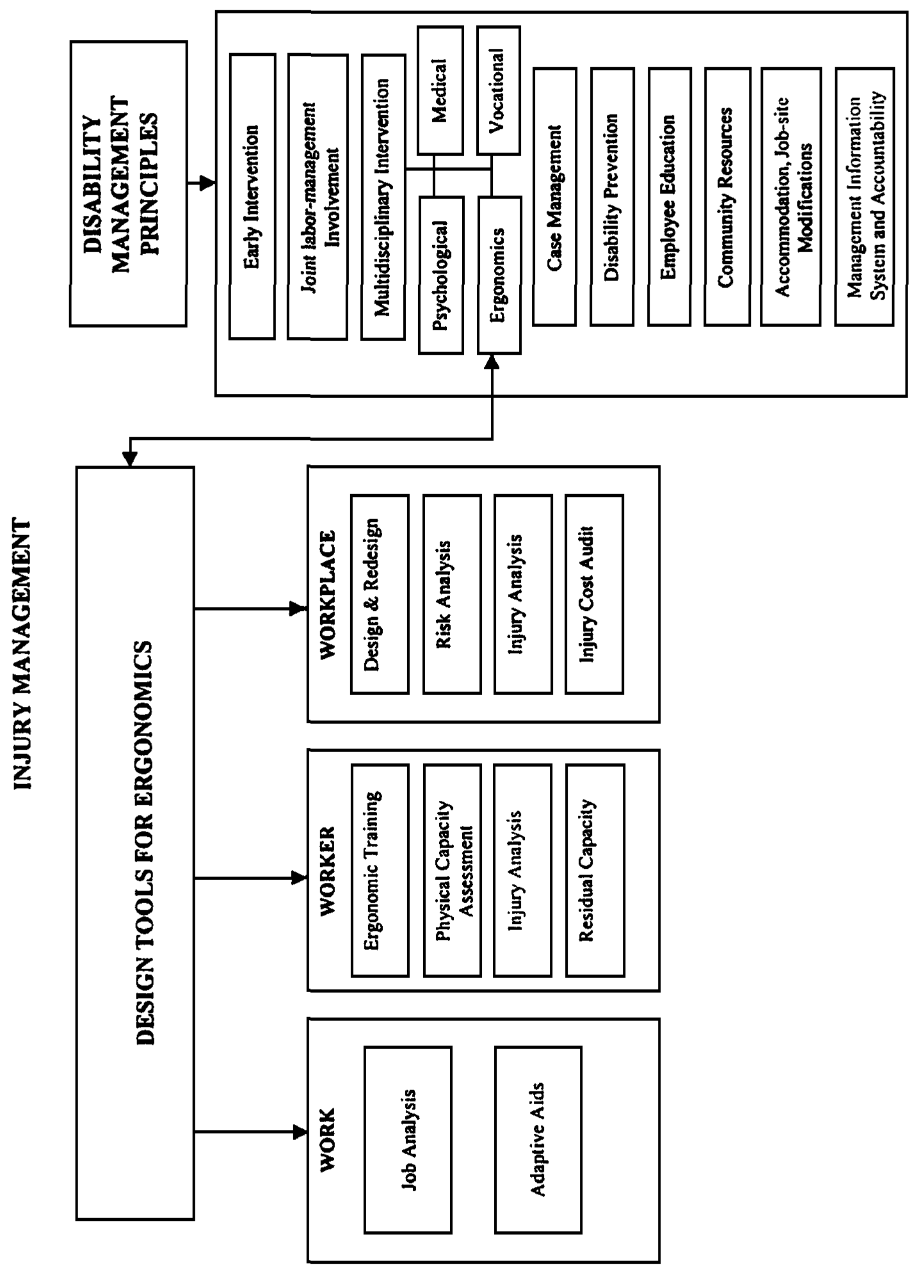

Fig. 9. Integrated injury management model.

each job classification, each affected work station, different age groups, both genders, and all work shifts. Incidence rates provide the following: (1) an indication about problem job classifications and problem workstations, (2) a relative ranking of jobs and workstations in terms of severity, (3) a priority list of jobs and/or workstations for hazard recognition efforts, (4) an understanding about how widespread the musculoskeletal injury/disorder problem really is in the workplace, and (5) an indication if the problem is influenced by age, gender, or shifts. It must be noted that rehabilitating the injured worker (and directing efforts towards the job/work station that caused injury to the worker) becomes a part of the focus in this approach. Even though the employees may not currently have any musculoskeletal problems or complaints, it is recommended that a thorough analysis of all jobs and the workplace be carried out to identify and prevent potential or future problems. Recent guidelines from the Department of Labors' Office of Workers' Compensation Programs (7) for return to work and work readiness programs recognize the facts that return to work programs are interdisciplinary and that occupational rehabilitation programs with any return to work plans must include biomechanical, neuromuscular, cardiovascular/metabolic, and psychosocial functions of the individual.

For purposes of our discussion, we will use the conclusions from injury trends presented in the previous section, and provide detailed information on other ergonomics steps involved in the injury management process. Industries must, however, set up their own injury data collection, recording, and analysis programs; proceed through all five steps highlighted above; and determine their own focus areas. In doing so, attention must be paid to the type of exposure or event leading to the injury (e.g., overexertion in lifting, contact with objects/equipment, falls, slips and trips); the specific natures of injury (e.g., sprain and strain, cuts, burns, laceration); the source of injuries (e.g., worker motion, floor or ground surface, parts and materials, tools); the occupation of the injured; age; gender; and part of body injured. Our emphasis is only on ergonomics interventions for musculoskeletal injuries of the back and the upper extremities.

Identification, Quantification, and Mitigation of Ergonomic Risk Factors

Ergonomics researchers have identified several risk factors associated with musculoskeletal overexertion injuries of the back and the upper extremities. It should be noted that the link between these risk factors and the occurrence of injuries and disorders in the workplace is not always based on causal relationships; more often than not, it is based on epidemiological and circumstantial evidence. Common risk factors for musculoskeletal injuries and disorders of the back and the upper extremities, as well as methods for their identification and quantification, are presented in the following sections.

Musculoskeletal Injuries/Disorders of the Back: Risk Factors and Their Mitigation

A number of work and working environment-related factors have been suggested by various researchers as risk factors in performing manual materials handling (mmh) activities, leading to overexertion musculoskeletal injuries and disorders. This section briefly reviews the outcome of many studies on each of these factors. The information contained in this section is based on extensive reviews of literature provided in (8) and (9).

Static work: Almost all activities involving materials handling contain a static and a dynamic component. Tasks, such as repetitive lifting tasks, have a dominating dynamic component, while tasks such as load holding have a dominating static component. The static work effort is characterized by contraction of muscles over extended periods of time (e.g., adopting a posture for extended periods of time). It has been shown that static work endurance is affected by work load and, therefore, static work should be avoided as much as possible.

Posture/technique: Body posture changes force requirements and may cause work to become very strenuous. Often the activity forces the body to assume different postures. The review of various studies shows that the stoop posture is advantageous when the load must be lifted repeatedly. The squat posture is desirable when the load can be fitted between the knees and is handled only occasionally. Loads that cannot be fitted between the knees and must be lifted repetitively should be handled by two individuals or must be moved with the help of a mechanical equipment. In general, it is recommended that one avoid: (1) extreme range of movements, (2) turning/twisting, (3) moving loads from the floor, (4) jerky motions, (5) fixed postures, (6) lifting loads to overreach heights, and (7) pulling loads. If possible, load movement should be restricted between knee and shoulder height. Pushing force should be exerted in near erect posture if possible, with handles located at a height of approximately 1 meter.

For heavy and awakward loads, the load should be lifted using the squat posture, the weight of the load should be less than the sum of the capacities of the individuals, and the people engaged in lifting should be similar in height. Coordination of the activity through counting or some sort of verbal signaling is also highly desirable.

Load characteristics: For greater stability, the characteristics of the load should be: (1) rigid and symmetrical in shape, (2) distributed uniformly, (3) if nonuniform, the heavier end should be closer to the body, (4) load center of gravity offset should be along the line joining the two hands, and (5) the heavier end should be held by the stronger arm. Also, the following recommendations should be followed: (1) the load dimension in the sagittal plane should not exceed 50 cm, (2) the load dimension between the hands should be minimized, (3) the load height should be determined by practical considerations such as body size and ability to clearly view obstructions in the path, and (4) the maximum load should not exceed 50 lbs for men and 44 lbs for women.

The limit for men is based on the revised NIOSH lifting guide (10); the limit for women is based on Mital *et al.* (9). It should be kept in mind that these load limits must be revised downwards when other risk factors, such as frequency, awkward object size, and asymmetrical lifting, are present.

Handles/couplings: Good handles or couplings are essential to provide load and postural stability during materials handling. Cut-out handles should: (1) be 115 mm long, (2) be 25–38 mm wide (or diameter, in case cylindrical handles can be provided), (3) have a 30–50 mm clearance all round the cylindrical handles, (4) have a pivot angle of 70° from the horizontal axis of the box, and (5) be located at diagnoally opposite ends to provide both vertical and horizontal stability for the load.

A reduction of up to 15% in the maximum load should be made if the containers or objects being handled do not have handles. In order to prevent slipping while carrying, pushing, or pulling, the coefficient of friction between the shoe sole and the floor should be at least 0.3 (preferable value of 0.5). In general, hardened rubber, dense vinyl plastic, or leather shoes provide a good coupling.

Frequency/repetivite handling: Materials handling activities that require frequent handling should either be redesigned to reduce the frequency, or mechanical equipment should be used to aid the handling. The revised NIOSH lifting guide does not recommend load handling frequencies of more than 10/minute if the work is to be done for 8 hours. The handling frequency can increase to 12/minute if the working duration is reduced to 2 hours. Practical considerations, however, may not allow such severe restrictions in the workplace. Therefore, an effort should be made to reduce the workload if higher frequencies are encountered. Studies by (9), (11), and (12) should be consulted if load handling frequencies higher than 12/minute are essential.

Asymmetrical handling/nonuniform loads: Handling objects asymmetrically is the rule rather than an exception in industrial settings. Asymmetrical materials handling leads to reduced load handling capabilities and strength, increased intra-abdominal and intra-discal (shear) pressures, and increased muscle activity of lower back muscles. The materials handler is advised not to keep the feet in a locked position. If the feet move the task is less stressful. The reduction in load lifting capability in such cases is expected to be no more than 15% for a 90° turning.

It is also important to realize that because most loads are not symmetrical, the stronger hand should be closer to the load center of gravity in order to reduce physical stresses on the hands and arms (please also refer to load characteristics and handles/coupling subsections).

Space confinement/restraints: Performing load handling activities with some form of spatial restraint is a common occurrence in industry. For loads that are to be placed on shelves, the shelf opening clearance for inserting boxes by hands should be approximately 30 mm. If the workplace layout does not allow erect posture (e.g., because of limited headroom, the load should be reduced by 1% for each degree of trunk flexion from the erect posture (maximum in the erect posture being 50 lbs for males and 44 lbs for females).

Environment: Adequate rest and replenishment of body fluids are essential when work is to be performed in hot climates. Cooling jackets may also be used to keep the core temperature from increasing. Protective equipment and clothing (i.e., shoes, gloves, vest and trousers, goggles, respirators, aprons and overalls, masks) should: (1) permit free movement, (2) be easily removable, and (3) allow for personal cooling (protection from body metabolic heat build-up). In addition, gloves should fit and allow maintenance of dexterity. Shoes should be nonslip type, comfortable, and water proof.

Working duration: The workload should be reduced as the working duration increases. The references (8), (9), and the model reported in (13) should be consulted to determine optimal work-rest profiles.

Work organization: Educating employees in safe procedures and reducing job demands (weight, frequency, reach requirements, rotation, and asymmetry) are essential to reduce the hazards of materials handling activities that are performed in workplaces that do not have adequate space. Allowing enough room to maneuver in the workplace and providing enough space for materials, shelves, tables, etc. are other prime requirements.

Fixed postures should be avoided (see the subsectionon posture) and the load handling activity should be redesigned to minimize static work component; otherwise, use of mechanical aids should be considered.

Adequate rest allowances should be provided to overcome the effect of fatigue. The procedure outlined in (8) should be used for this purpose. Job rotation should be considered to minimize monotony, inattentiveness, and fatigue on a specific group of muscles. While considering job rotation, attention should be paid to task sequencing; a physically demanding task should not follow another physically demanding task without adequate rest.

Musculoskeletal Injuries/Disorders of the Upper Extremities: Risk Factors and Their Mitigation

As in the case of the lower back, a number of work-related factors have been identified as occupational risk factors that cause musculoskeletal injuries and disorders in the upper extremities. Tichauer and Gage (14), Armstrong (15), Putz-Anderson (16), Mital and Kilbom (17–18), Westgaard *et al.* (19), and Kuorinka and Forcier (20) have listed these factors, and also what actions should be taken to eliminate or reduce musculoskeletal injuries and disorders associated with these factors. The problems associated with the upper extremity risk factors and the recommended actions are summarized in this section.

Fit, reach, and vision: The inability of individuals to fit in the workplace, to reach objects and hand tools, and see without obstruction can force them to adopt postures and sustain loads that can cause musculoskeletal injuries or aggravate such disorders. The workplace should accommodate large as well as small people. The work, objects, and tools should be located such that there is no need to lean forward, flex the torso, flex neck/shoulder, or extend arms/hands beyond reach. The work, objects, and tools should also be clearly visible.

Cold, vibration, and local mechanical stress: Colder working climates have been associated with carpal tunnel syndrome. It is, however, not clear if the occurrence of carpal tunnel syndrome is due to cold temperatures or to gloves that are worn when working in colder climates. Because cold temperatures reduce blood flow to hands, sensitivity of motor and sensory nerves is reduced. This causes greater exertion of force and increased activation of muscles. The increased activation of muscles is a more likely contributor to carpal tunnel risk than gloves.

Circumstantial and epidemiological evidence indicates that workers who are exposed to hand-arm vibration have a greater risk of injury and musculoskeletal disorders than those who are not. Vibration causes overgripping of the object to maintain control, increased forearm muscle activation, and higher muscle loads. In combination with repetitive work, vibration is considered to aggravate musculoskeletal disorders. In general, it is advisable to avoid segmental vibration (vibration entering the body from the hands) below 1000 Hz. Specifically, hand-arm vibrations in the 2 to 200 Hz range should be avoided (18,21).

Local stresses, such as pressure concentration points resulting from manipulating external objects (e.g., pressure caused by uneven surface projections) can cause injury to nerves, blood vessels, and skin. To avoid these disorders, the following recommendations should be followed: (1) enlarge contact area, (2) reduce pressure, (3) avoid leaning against the wrists, hands, and elbows, and (4) minimize impact loads, such as when using hammers, nut drivers, or chain saws.

Awkward postures: Extreme postures (postures closer to the end of the joint motion range) can cause: (1) extension/flexion and ulnar/radial deviations of the wrists, (2) flexion/extension and pronation/supination of the elbows, (3) flexion/extension and abduction/adduction of the shoulders, and (4) flexion/extension of the neck. This could lead to: (1) discomfort and joint stresses, (2) reduced blood flow, (3) high muscle forces, (4) fatigue, (5) reduced endurance (working) time, (6) acute shoulder and neck pain, (7) shoulder tendinitis, (8) carpal tunnel syndrome, and (9) increased sick leave.

The following should be avoided as much as possible: (1) hands above the shoulder height, (2) shoulder elevation, (3) shoulder abduction of more than 30°, (4) repetitive shoulder flexion, (5) overhead reaching, (6) elbow/forearm pronation, (7) wrist flexion/extension exposure of more than 20 hours/week, (8) wrist deviations of more than 20°, and (9) wrist extension/flexion.

Also, there is some evidence to suggest that hand manipulations should not exceed 1000/ hour for males and 750/ hour for females (22). Furthermore, some researchers suggest that high demands on time (more than 4 hours distributed over the entire day or more than 30 minutes continuously or repetitively) in combination with high force or precision requirements should be considered unacceptable. However, other researchers believe that such suggestions require more evidence. Wrists should be in the neutral posture (as when shaking hands); slight ulnar deviation (7° ± 2) and wrist extension (up to 20°) may be permitted.

Musculoskeletal and mechanical load: Exertion of force has been associated with musculoskeletal injuries and disorders. While there have been many studies investigating the association between force and musculoskeletal injuries and disorders, only a few have provided a specific value; many have only provided a qualitative assessment of force. From those studies that have included quantitative values of force (16,17,18,19), it has been concluded that the grip force should not exceed 40–50% of the maximum grip strength. Hand tools should not weight more than 5 lbs; preferably, the weight should be just under 4 lbs. Pinch type of grips should be avoided when applying force as it requires up to 5 times more force than a power grip (such as when using a hammer).

The following grip size should be used: (1) thickness—50–60 mm for power, 8–13 mm for precision, (2) length—minimum 120 mm for power, minimum 100 mm for precision, minimum 125 mm with gloves, (3) guard—minimum 16 mm, (4) shape—noncylindrical, preferably triangular with 110 mm periphery, (5) force—100 N maximum for power, and (8) handle bent—10° for power. For details, refer to Mital and Kilbom (17,18).

Repetition has been associated with the risk of musculoskeletal injuries and disorders. There is evidence that as few as 7,000 hand movements a day could be risky (15). Other researchers have recommended a higher number (see Mital and Kilbom (18); Kuorinka and Forcier (20)). It should be kept in mind that repetition is not the only factor in the workplace. Usually, repetitive motions involve force exertions and awkward postures. What combinations of these factors are acceptable is not known. Further, if two of these three factors are not relevant in a work situation, what values of the remaining risk factor are acceptable is also not very well known (also see subsection on posture).

The duration of work has also been recognized as a risk factor. The demands on time can be divided into three categories:(1) low (less than 1 hour distributed over the entire day or less than 10 minutes continuously or repetitively), (2) moderate (1 to 4 hours distributed over the entire day or 10 to 30 minutes continuously or repetitively), and (3) high (more than 4 hours over the entire day or more than 30 minutes continuously or repetitively).

High demands in combination with precision or high force requirements should be avoided. If work is performed continuously until exhaustion at 25% of maximum voluntary contraction (maximum volitional strength), recovery does not take place even after 24 hours.

Static load/work: In general, the ergonomics literature recommends avoiding static load and posture. In a static posture or when supporting a static load, the body is unable to meet the metabolic energy requirements (impaired blood circulation) because of a lack of muscle movement. Static loads and postures also lead to rapid fatigue, pain, impaired nerve conduction, and chronic muscle damage. Postures that are maintained for even as short a duration as one minute may be considered fixed. It should be ascertained that such postural fixity (body in a fixed posture) is not caused by the need to support the equipment, tool, or workpiece.

Task invariability: Task invariability has both physiological and psychological connotations. Psychologically, repetitive work leads to monotony and boredom. Physiologically, it could lead to smaller range of motions (postural fixity), pain and discomfort (particularly in torso, legs, and feet because of prolonged sitting or standing), and slower movements. Wherever and whenever possible, work should include variety in terms of posture, motions, etc.

Cognitive demands: Mental effort can cause neck muscle tension and stress in general as there is significant need for eye fixation for prolonged periods of time.

Work organization: Please refer to the discussion under risk factors for the lower back. Self-pacing is preferable to machine pacing as it allows workers to control the frequency at which a task is performed without the stress imposed by machine pacing. From a frequency standpoint, incentive systems such as piece rate systems should not be encouraged. Overtime, particularly unwanted overtime, also has a negative impact on worker health. Night shifts should be immediately followed by days off as the body needs to recover from the maximum disturbance to the circadian rhythms.

Methods for Identifying Musculoskeletal Injury Risk Factors

Before using specific techniques to recognize hazards, it is important to find out as much information about the job and people performing it as possible. This procedure, known as job analysis, can be carried out in two different ways: (1) by conducting a methods study, a popular tool used by industrial engineers and (2) by using checklists. Both methods are briefly described below (For details, please refer to any book on work measurement or motion and time study. Some references are as follows: Konz (23); Karger and Hancock (24); and Niebel (25)).

Methods Study. Methods study is the systematic recording and critical examination of existing ways (proposed ways in case of new jobs) of doing work, as a means of developing and applying safer, easier, and more effective methods and reducing overall costs. It is normally done at two levels: (1) recording work sequence using a flow process chart, and (2) recording work sequence using the techniques of micromotion study.

The second method of recording work place movements is used for very short cycle jobs and does require filming the job. The recording of facts about a job using a flow process chart is accomplished with the aid of five symbols:

○ (operation), □ (inspection), ⇨ (transport), D (delay), and ∇ (permanent storage)

Once the job details are recorded, the recorded activities are examined critically (unfortunately, this very important step is not covered in most ergonomics publications). The questioning sequence should follow a pattern that examines the purpose (for which), the place (at which), the sequence (in which), the person (by whom), and the means (by which) the activities are undertaken with a view to eliminating, combinig, rearranging, or simplifying those activities. The idea is to systematically examine every activity recorded for the purpose, place, sequence, person, and means. The primary questions are as following: (1) What is being done? (2) Why is it being done (purpose)? (3) Where is it being done (place)? (4) When is it being done (sequence)? (5) Who is doing it (person)? (6) How is it being done (means)? Once these primary questions are answered, the second stage of questioning is undertaken. In this stage, options (what else?) are sought. The following questions are asked: (1) What else might be done and what else should be done (purpose)? (2) Where else it might be done and where should it be done (place)? (3) When might it be done and when should it be done (sequence)? (4) Who else might do it and who should do it (person)? (5) How else might it be done and how should it be done (means)? The success of methods study depends upon accurately recording and answering these questions.

For jobs that have very short cycle time (typically, in seconds) and that are repeated thousands of times (such as assembly operations), recording greater details is necessary. The job is filmed and subjected to micromotion study. All activities are divided into fundamental motions known as therbligs. This is done by playing and analyzing the film or videotape, frame-by-frame. Once the job has been recorded, the contents should be analyzed for risk factors. Checksheets, such as the one shown in Tables I and II, may be used for this purpose.

Checklists. As an alternative to methods study, or as a supplement to it, checklists may be used to conduct job analysis. The hazard recognition techniques, described in the next section, should be used in conjunction with checklists to identify risk factors and the extent to which they may potentially contribute to the problem. The main question is "which checklist should be used?" In fact, a number of checklists have been developed and range from very simple (26) to elaborate (27). Many companies, depending upon their need, develop their own checklist. Table I shows a very general checklist modified from Dul and Weerdmeester (26) and Kellerman *et al.* (27). A checklist more specific to upper extremities is provided in Table II (28).

As these two checklists illustrate, the amount of information provided by a checklist varies considerably and is determined by the nature of questions asked. Considerable attention should be given to developing a checklist. One may begin with the development of an exhaustive checklist and then eliminate unnecessary questions systematically. One should realize that gathering information in this manner can be time consuming and expensive as one may end up gathering irrelevant information. An efficient checklist, therefore, is a very important tool. Where exactly the balance between detail and cost/time lies varies from situation to situation. One must question the necessity for the level of detail (people love details but are they necessary?) and how it helps in understanding and eventually solving the problem. Once the information has been gathered with the help of the checklist, it should be analyzed for the answers (yes, no, quantitative, etc.) to identify the risk factors, problems, and others so that appropriate control actions may be initiated.

Methods for Measurement and Quantification of Musculoskeletal Injury Risk Factors

The techniques to assess risk factors associated with musculoskeletal injuries and disorders are broadly classified as follows: (1) biomechanical techniques, (2) physiological techniques, and (3) psychophysical techniques. Some of these techniques are quantitative and some provide qualitative information.

Biomechanical Techniques. These techniques focus on assessing forces/stresses and motions that are generated as a result of performing specific activities.

Spinal stresses: Spinal stresses (compressive and shear) provide an indication of the hazard the body is subjected to while handling loads. A number of biomechanical models

Table I. A Simple Ergonomics Checklist for Eliminating Injuries

1.	Has a tall man enough room?	Y	N
2.	Can a petite woman reach everything?	Y	N
3.	Are excessive reaches avoided?	Y	N
4.	Is the work within normal reach of arms/legs?	Y	N
5.	Can the worker sit on a good chair (back, seat, height)?	Y	N
6.	Is standing alternated with sitting and walking?	Y	N
7.	Is an armrest necessary? Is it good (adjustable, supports arms without pinching, doesn't restrict movement, etc.)?	Y	N
8.	Is a footrest required? Is it good (adjustable, supports load, stable, etc.)?	Y	N
9.	Is it possible to vary the working posture?	Y	N
10.	Is there enough clearance for knees? Feet?	Y	N
11.	Is the distance between eyes and work correct?	Y	N
12.	Is the work height adjustable?	Y	N
13.	Has the use of platforms been avoided?	Y	N
14.	Is static work avoided as much as possible?	Y	N
15.	Are vises, jigs, conveyor belts, etc., used wherever possible?	Y	N
16.	Where protracted muscle loading is unavoidable, is the static strength required less than 10% of the maximum?	Y	N
17.	Is the dynamic strength required for protracted work less than 5% of the maximum?	Y	N
18.	Are power sources employed wherever possible?	Y	N
19.	Has the number of muscle groups employed been minimized with the help of counterbalance?	Y	N
20.	Are torques around the axis of the body avoided as far as possible?	Y	N
21.	Is the direction of motion as correct as possible in relation to the amount of force required?	Y	N
22.	Are loads that are lifted/carried with two hands below 50 lbs for men? Below 44 lbs for women?	Y	N
23.	Are the joints in a neutral position?	Y	N
24.	Is the work held close to the body?	Y	N
25.	Are forward-bending postures avoided?	Y	N
26.	Are twisted trunk postures avoided?	Y	N
27.	Are sudden and jerky movements/forces avoided?	Y	N
28.	Is there a variation in postures and movements?	Y	N
29.	Is the duration of any continuous muscular effort limited?	Y	N
30.	Is muscle exhaustion avoided?	Y	N
31.	Is rest taken after heavy work?	Y	N
32.	Are breaks sufficiently short to allow them to be distributed over the working duration?	Y	N
33.	Are hand-held tools too heavy?	Y	N
34.	Are tools maintained properly?	Y	N
35.	Is the tool grip of proper size (length, diameter, etc.)?	Y	N
36.	Has work above the shoulder been avoided?	Y	N
37.	Has work with hands behind the shoulders been avoided?	Y	N

Note. These questions can be expanded and made more specific by including quantitative information for different risk factors.

have been developed to assess these stresses. Dynamic three-dimensional biomechanical models are more accurate in comparison to static 2-D or 3-D models. Even though several biomechanical models are available, most are complex and not user friendly; only a handful can be used by people at large, particularly those in industry. Two such models are briefly described.

However, before these models are used, it is essential to understand the limitations of these and any other existing biomechanical model. Static models consider the motion of the human body as a series of static postures and perform static analysis in each posture to determine musculoskeletal stresses. Dynamic models account for the inertial effects of

Table II. Upper Extremity Checklist (Modified from Keyserling WM, Stetson DS, Silverstein BA, Brouwer ML (*Ergonomics* 1993; 36(7):807–831))

Worker information			
Which hand is the operator's dominant hand? (circle one)	Left hand	Right hand	Both hands
Circle a, *, √ or 0 to answer each question below:			
Repetitiveness			
1. Does the job involve repetitive use of the hands and wrists? Answer "yes" if either of the following is true a. the work cycle is less than 30 seconds long, or b. the hands repeat the same motions/exertions for more than 1/2 of the work cycle.		No	Yes

Mechanical Stress	Left hand		Right hand		
2. Do the hands or sharp objects, tools, or part of the workstation put localized pressure on:	no	yes	no	yes	element
a. back or side of the fingers?	0	√	0	√	———
b. palm or base of the hand?	0	√	0	√	———
c. forearm or elbow?	0	√	0	√	———
d. armpit?	0	√	0	√	———
3. Is the palm or base of the hand used as a striking tool (like a hammer)?	0	√	0	√	———
Force					
4. Does the worker lift, carry, push, or pull objects weighing more than 4.5 kg (10 lbs)?	0	√	0	√	———
5. Does the operator grip an object or a tool that has a smooth, slippery surface (no texture or hand holds to reduce slipping)?	0	√	0	√	———
6. Is the tip of a finger or thumb used as a pressing or pushing tool?	0	√	0	√	———
7. Check blank if no gloves are worn and skip question	———				
If the operator wears gloves, do the gloves hinder gripping?	0	√	0	√	———

	Left hand			Right hand			
	no	some	more than 1/3 cycle	no	some	more than 1/3 cycle	element
8. Does the operator grip or hold a part or a tool that weighs more than 2.7 kg (6 lbs) per hand?	0	√	*	0	√	*	———
Posture							
9. Is a pinch grip used?	0	√	*	0	√	*	———
10. Is there wrist deviation?	0	√	*	0	√	*	———
11. Is there twisting, rotating, or screwing motion of the forearm?	0	√	*	0	√	*	———
12. Is there reaching down and behind the torso?	0	√	*	0	√	*	———
13. Is an elbow used at or above mid-torso level?	0	√	*	0	√	*	———
Tools, Hand-held Objects, and Equipment							
14. Is vibration from the tool or object transmitted to the operator's hand?	0	√	*	0	√	*	———
15. Does cold exhaust air blow on the hand or wrist?	0	√	*	0	√	*	———
16. Is a finger used in a rapid triggering motion?	0	√	*	0	√	*	———
	no	yes		no	yes		
17. Is the tool or object unbalanced?	0	√		0	√		
18. Does the tool or object jerk the hand?	0	√		0	√		

List all tools, objects, and equipment used to answer questions 14–18.

Tool Score = (No. of *'s) × (No. of √'s) = Comments:

the body segments and the loading that results from acceleration. Static analyses seriously underestimate the spinal stresses, by as much as 40 to 50%, as the effect of the inertial forces is neglected. Dynamic models, however, introduce complexity in terms of the input data acquisition required. It should also be realized that the utility of biomechanical models is greater for comparative task analysis than for stand-alone task analysis to determine absolute load values. Most of the models compare the model generated spinal stresses with the load tolerance capability of the human spine (cadaver spines) to estimate the factor of safety. Because the human tissue tolerance capability under dynamic conditions is not known, we only get a relative assessment of different tasks and task conditions or an approximate idea of the hazard.

Static strength biomechanical models, such as the one described in Chaffin and Anderson (29), predict the population capable of performing each task from a variety of inputs: body posture, object, force needed to oppose the object (average, maximum), and location of the hands.

Three-dimensional dynamic biomechanical models, such as the one described in Kromodihardjo and Mital (30,31), can handle both symmetrical and asymmetrical manual lifting tasks and require minimal input (worker's body size, load, type of task) to determine spinal stresses and the factor of safety.

Risk potential for manual handling activities: The models discussed in the previous section are limited to manual lifting activities that are performed infrequently or occasionally. Most industrial jobs, however, are not pure lifting jobs; they involve a variety of handling activities, such as carrying and pushing, in a variety of combinations. Frequently, it is interesting to find the risk of musculoskeletal injury associated with such task. To date, one model has been developed that can handle analysis of a diverse multiple activity manual handling job. This model has undergone a number of revisions, the latest described by Mital (32). The model is based on the materials handling guide developed by Mital *et al.* (9) and takes into consideration such factors as: worker gender, population percentile, types of task (lifting, lowering, pushing, pulling, and carrying), working duration, load symmetry/asymmetry, symmetrical/asymmetrical handling, handling in hot climate, postural/spatial restraints, and presence/absence of coupling. The risk factor for each manual handling is calculated by comparing actual and recommended workloads. Recommended workloads are based on a combination of biomechanical, epidemiological, physiological, and psychophysical design criteria.

Body strengths: Human strengths are a primary measure of an individual's physical capabilities, particularly those that permit a person to exert force or sustain external loading without inflicting personal injury. As stated under the risk factors section, jobs that are static in nature and are performed for prolonged periods of time (something that should be avoided) should not require more than 10% of a person's maximum voluntary contraction (MVC); some recommendations limit this exertion to no more than 2 to 3%. For prolonged dynamic tasks, the strength requirements should not exceed 5% of MVC. The extent of static or dynamic effort should be compared with MVC to determine how potentially hazardous the job is. The techniques to measure effort on the job are described later in the force subsection.

Static (also known as isometric) strengths are the capabilities of muscles to produce force or torque by a single maximal voluntary exertion, such that the length of the muscle remains unchanged (zero displacement). Because the posture assumed by the worker influences strength, it is necessary to specify the posture during strength measurement. Static strength measurement requires that individuals build-up their muscular exertion against a fixed resistance slowly over a 4- to 6-second period, without jerking, and maintain the peak exertion for about 3 seconds. A rest break of at least 30 seconds is provided between successive exertions; 2 minutes if necessary. No external motivation is provided. The peak strength, thus recorded, is the MVC of the individual.

Several different kinds of dynamic strengths have been defined in the literature. The two strengths that are most relevant are isokinetic strength and isoinertial strength. Isokinetic strength is the measure of MVC when the involved body segments move at a constant speed. Speed control is achieved by a mechanical or hydraulic device that does not allow the body segment to move faster than the preselected speed, the prime requirement of isokinetic strength measurement. The worker is asked to assume the required posture, including arm reach distance and arm orientation. Once the worker is ready, he/she is required to exert (pull) the handle to exert as much force as possible without jerking. The speed of exertion is set such that it simulates the speed of the task. The maximum force of exertion is recorded. Rest breaks between successive exertions must be provided, and the posture, speed of exertion, arm orientation, reach distance, and population must be reported with the data.

Isoinertial strength measures the ability of a person to overcome the initial static resistance by measuring the maximum amount of weight he or she can handle and move to an assigned point at a freely chosen speed. Actual speed of movement varies within the specified range of movement. Maximum weight can be determined by incrementing weights (as high as 25 lbs or as small as 2.5 lbs). Initial increments are large (maximum) and if the effort fails, the increment is reduced by half. It should be noted that this strength is not MVC and can be measured with the help of a container and graduated loads. Furthermore, the technique has the disadvantage of risk-exposure, particularly in the upper reach regions where the human strengths are much lower compared to strengths at lower heights (mid-body region or lower). It is, therefore, likely that the pain tolerance may not be distinguished from trauma. The details of strength testing are given by Chaffin (33), Mital and Das (34), and Mital *et al.* (35).

Videotaping: Videotapes are ideal for recording operators' methods and elapsed time. A careful analysis of tapes provides a wealth of information about several risk factors through micromotion study including posture, cycle time, frequency, and accelerations. From these data, information about forces, joint angles, etc., can be obtained.

At least five cycles of the task should be filmed. If possible, the job and the operator should be filmed from the front, both sides, rear, and at an angle from the front-above (3/4th exposure above the operator's head height). Once the job has been videotaped, the tape can be played back for micromotion analysis and recording of risk factors. As stated earlier, any standard text on motion and time study provides details of micromotion analysis procedures (see Niebel (25)). The procedure involves breaking the job cycle into basic motion elements described by therbligs. The number of frames an activity takes and the speed of videotaping provide the time the activity takes. The tape can also be used to provide body and body segment angles (multiple views are needed for this) and body joint accelerations (some calculations are needed and are described under the force subsection).

Posture: Posture is the configuration the human body assumes during the course of an activity. Usually, it is necessary to record postures in a 3-D configuration. The simplest form of posture recording can be made through photographs. Typically, the worker would have a grid pattern (ex., one-inch squares) as the background. This grid can be used to assess joint and limb angles and reach distances in the plane of interest. However, the body joints must be clearly marked. Joint and limb angles in the vertical and horizontal planes can also be measured using a variety of goniometers (for fingers, limbs, etc.). The posture can be graphically depicted if the limb and joint angles and limb lengths are recorded. The posture, thus recorded, is not very accurate but suffices for practical purposes.

There are several other methods that record the posture by recording its deviation from some basic postures. One of the popular methods is posture targeting (36). The procedure makes use of a diagram (Fig. 10), which has "targets" located alongside each of the major limb segments, on the head, and on the trunk. Making the form requires the user to take the posture shown in Fig. 10 as the zero position. Forward movements by limbs, trunk, or head (in the forward-backward plane) require a mark along the vertical axis of the target ("up"

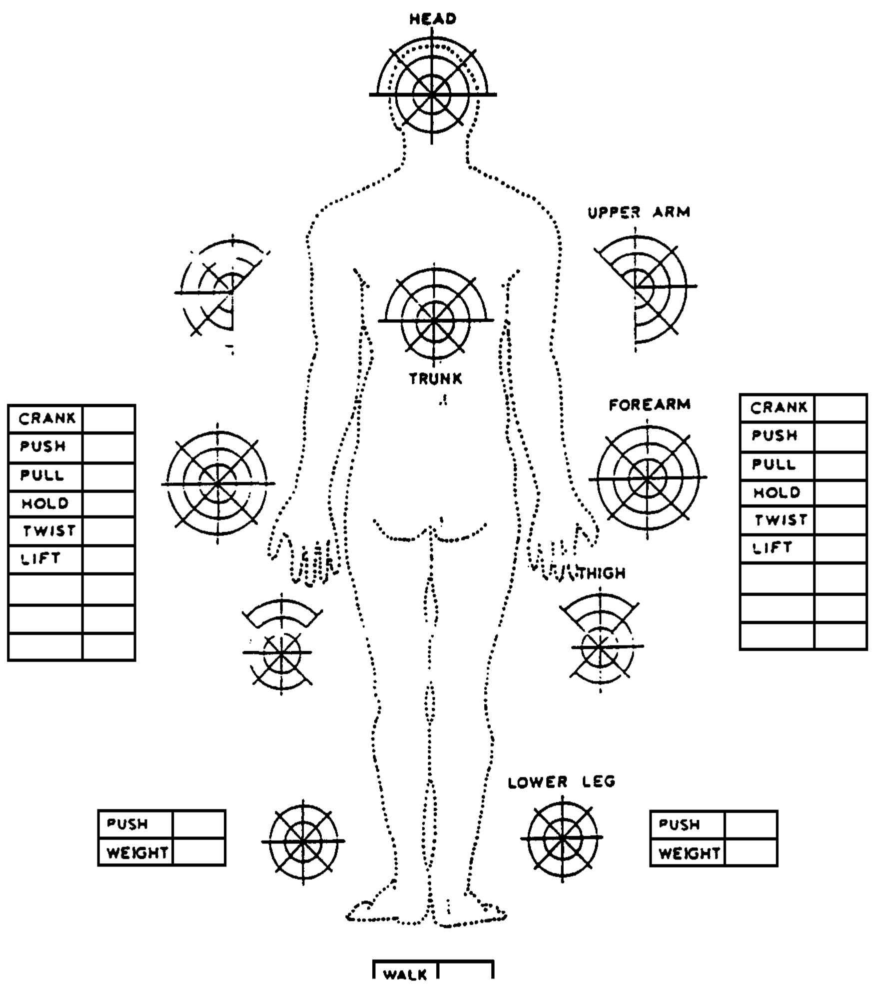

Fig. 10. Posture targets with zero position shown by the dotted line (modified from Corlett EN, Madley SJ, Manenica I. Postural targeting: a technique for recording working posture (*Ergonomics* 1979; 22: 357–366)).

for forward) and positioning on that axis according to the estimated angle of displacement. Each concentric circle represents a 45° angle. Displacements to the side of the body are marked on the horizontal axis according to the estimated angle. Directions in a horizontal plane are marked along the appropriate radius or between appropriate radii.

Another method is the "Penguin" method developed by Kroemer (37). It encompasses major body segments, and can be enhanced to include fingers and head. For each segment, a number of preselected positions are shown (more variations of these positions can be included). The observer marks the penguin that most closely resembles the actual working posture. A computer program is available from the developer and provides angles, curvatures, and directions associated with the selected posture.

There are many other methods available to record posture. Many commercial systems have also been developed. While most of these other methods are time consuming, laborious, and inefficient, commercially available systems are expensive, particularly if dynamic postures are to be recorded. For most practical purposes, such methods and systems are not necessary and static posture recording techniques described above are sufficient.

In addition to the techniques described above, joint angles (and hence postures) can be measured by a goniometer. A variety of goniometers are available for measuring finger and other body segment flexion/extension, and include the mechanical analog and digital types.

Body size measurements: Linear body dimensions, such as limb lengths and stature, are needed to determine the worker fit in the workplace. Such measurements and others, such as reach, can be made by using anthropometers and anthropometric tape. The use of these devices is straightforward. For a description of some standard measurements, the reader is referred to Roebuck (38) and Pheasant (39).

Force: Force exerted on workpieces, tools, and other objects in the workplace can be measured in several different ways. The simplest way is to have the operator exert force equivalent to that exerted during his/her job performance on a force transducer (dynamometer). Such methods are reasonably reliable, accurate, quick, simple, and inexpensive. A variety of force measuring transducers/dynamometers is available from the market, and are capable of measuring force exerted by body limbs (hand, arm, finger, feet, whole body) in different postures and grips.

The second method, not mentioned in ergonomics literature, involves the determination of limb acceleration followed by computation of the force by multiplying the acceleration by the mass of the limb or object. Numerical differentiation of displacement data obtained from videotape recording is needed to do this. The technique is described in some detail below.

The object, or joint, where force needs to be measured should be marked prominently (either at the center or at the edge). This mark is videotaped while in motion. The actual distance between the starting and ending points is also recorded. This actual distance and the distance between the same two points when seen on a monitor (film distance) are used to establish the scaling (size) factor (scaling factor S = actual distance between starting and ending points/distance between the same points as measured on the monitor screen). Because the speed of the videotape is known, the time elapsed between successive frames is also known (1/film speed; for 120 Hz speed, time elapsed between successive frames, h, is 1/120 second; note that the system has only 1 image per frame—in the event it has 2 images per frame, time per image will be 1/120 second). The videotape is advanced one frame (image) at a time and the screen displacement of the mark from the starting position is recorded.

This displacement is multiplied by the scaling factor to obtain the actual displacement. The displacement associated with the first frame (image) is y_1 and with the nth frame (image), y_n; n is the number of frames (images) required from the starting point to the ending point. From these y_i values ($i = 1$ to n), velocity V_i and acceleration A_i for the ith frame (image) are calculated as follows (forward difference method):

$$V_i = (-y_{i+2} + 4y_{i+1} - 3y_i)/2h; \qquad A_i = (-V_{i+2} + 4V_{i+1} - 3V_i)/2h$$

Note that when $i = (n - 1)$ or n, data for $(i + 1)$th and/or $(i + 2)$th frames will not be available. These frames can either be ignored or a backward difference method can be used. Because we generally are interested in finding peak forces, peak accelerations are of interest. In most cases, peak accelerations take place somewhere betwen the starting and ending points and the loss of this information, if the last 2 frames (images) are ignored, is not significant.

Once the acceleration values are computed, one may want to average them, provided it can be ascertained that acceleration during the motion remains constant (for example, when motion is due to gravity); averaging, otherwise, will cause error. Further, it should be noted that errors made in computing displacement are magnified several times because of numerical differentiation. Great care, therefore, should be exercised in recording displacement data. The acceleration data now can be multiplied by mass to obtain force. If the object is external, it can be weighed. For limbs, mass data are provided by Roebuck *et al.* (40), Roebuck (38), and Pheasant (39).

The third method for measuring force, electromyography, is the most commonly recommended in ergonomics literature. It must be noted before using EMG that in many situations it is not appropriate to even use surface electrodes. However, because the technique has been mentioned frequently in the ergonomics literature, it is described here briefly.

When muscles contract, myoelectric signals occur. Electromyography (EMG) is the recording and analysis of these signals. EMG can be used to assess the level of muscular activity as well as to evaluate work and performance. Generally, EMG is best suited for nonrepetitive work where the activity of specific muscles is of interest. The EMG signal can provide four kinds of information (41): (1) whether or not a muscle was in use during an activity, (2) relative level of muscle activity, providing exertion (effort) level (not force), (3) force generated by the muscle under static or constant velocity, and (4) muscle fatigue as indicated by the shift of frequency spectrum to lower levels.

However, there are primarily two kinds of EMG analysis that may be of interest in industry: amplitude analysis and frequency analysis. Amplitude analysis provides a measure of muscle activity for different tasks and individuals, while frequency analysis provides an evaluation of the fatigue state of the muscle. In both cases, the EMG signal must be normalized with respect to a reference isometric MVC, and expressed as a % of the maximum voluntary contraction (MVC) as follows:

$$\text{Relative muscle activity} = \{(\text{task EMG-resting EMG})/(\text{Maximum EMG-resting EMG})\}$$

Such normalization permits comparison across different tasks and people. Whenever possible, the MVC of the muscle of interest should be recorded in a position simulating the actual task position. Subtraction of resting muscle EMG from both activity and MVC provides a measure of task specific muscle activity.

For muscle fatigue investigations, the frequency spectrum needs to be normalized. Because during fatigue the frequency spectrum shifts downwards, normalization is performed over the lower frequency ranges. The amount of frequency signal in a specific range during the state of fatigue is divided by the amount of frequency signal in that range during the beginning of the activity.

Even though three different kinds of electrodes are available (surface, pin, and wire), surface electrodes are adequate for industrial activities. In most situations, surface electrodes are used in pairs with a third one for ground. Two kinds of surface electrodes are commonly used: dry or active electrodes, which do not require skin preparation; and passive electrodes, which require cleaning of the electrodes, application of a saline gel between the electrode and skin, and skin preparation (cleaning and light abrasion of the skin at the electrode application site). Active electrodes are preferable because they are not only convenient to use but also provide relatively greater signal fidelity (accurate transmission).

Once the electrodes are prepared, the application location must be selected. The location chosen should yield the highest signal amplitude. Generally, the electrode should be located in the region halfway between the center of the innervation zone and further tendon. For analysis and interpretation, the electrode signal needs to be amplified by preamplifiers and main amplifiers, filtered, and conditioned, depending upon the need (force information, frequency information, etc.). For further information on this technique, refer to NIOSH (41) and Basmajian and DeLuca (42).

EMG recording equipment can be obtained from a variety of medical equipment manufacturers. The basic set consists of electrodes, preamplifiers, amplifiers, filters, oscilloscope, analog-digital converters, and computers for data processing and analysis.

Vibration: Basically, vibration of man is measured in acceleration units m/s^2 r.m.s. of a 1/3 octave frequency band (or possibly 1 octave bands for hand-arm vibration) over the frequency range of interest. The level of vibration may also be quoted in logarithmic units in terms of dB re 1 $\mu m/s^2$. Vibration is more critical for upper extremity musculoskeletal injuries and disorders and, therefore, in this subsection the focus will be on hand-arm vibration.

The usual equipment for measuring vibration amplitude is piezoelectric accelerometers, which can measure frequencies within the range of 1 to 50,000 Hz. When the accelerometer is exposed to vibration, it moves the stylus against a crystal element, which produces an electrical voltage proportional to the compression of the stylus against the crystal element. This voltage is proportional to the acceleration. A charge amplifier is used to make up for any signal loss.

It is important to indicate whether the vibration is being measured on an impact (e.g., chain saw, grinders, pneumatic wrenches) or nonimpact-type tool (e.g., chipping hammers, jack hammers). Shock accelerometers, which have a special filters to attenuate impulse vibration signals, should be used to measure vibration amplitudes of nonimpact type tools.

Many commercially available accelerometers are available and weigh as little as 5 gm. A typical Bruel & Kjaer accelerometer may weigh about 40 gm. The selection of an accelerometer should be done carefully, with consideration given to low amplitudes. The vibration measurements must be made in three independent axes at 90° to each other (orthogonal axes). A triaxial accelerometer, which measures vibration in 3 axes, can also be used instead of three accelerometers. NIOSH (21) provides some recommendations for mounting locations. Generally, the accelerometers should be mounted to the surface where the maximum vibration energy enters the hand. For assessing vibration exposure to hand, the largest of the rms acceleration amplitudes along the three orthogonal axes may be used. The vibration exposure should also be characterized by the duration of exposure and kind of coupling between the tool and the hand (tight or loose). The guidelines for vibration assessment are based on time-averaged, frequency-weighted rms acceleration levels.

The cost of an accelerometer can vary considerably, from less than a hundred to several thousand dollars, depending upon its sensitivity and weight. Therefore, careful consideration should be given to choosing an accelerometer.

Physiological Techniques. Physiological techniques are suitable for repetitive and whole body work such as manual materials handling. The two human body responses that indicate the extent of hazard and respond to various risk factors presented in a previous section are oxygen consumption and heart rate. The following subsections describe how each can be measured and how each is related to risk.

Oxygen consumption: Oxygen consumed by an individual is influenced by the intensity of the task he/she performs. Typically, oxygen consumption is compared with the physical work capacity (PWC; also known as aerobic capacity, maximum aerobic power, and maximum oxygen uptake-Vo_2 Max). PWC is the maximum amount of oxygen that an individual can consume per minute (maximum oxygen uptake/minute). The higher the percentage of PWC a task requires, the higher the resulting physical stress, fatigue, and possibility of injury.

PWC can be measured by maximal or submaximal methods (43). In the maximal method, the worker is stressed to the maximum and oxygen consumption at that level is recorded. In submaximal methods, which are more commonly used, individuals are required to perform at least three workloads on either a bicycle ergometer or a treadmill. The use of a treadmill is preferable for two reasons: (1) walking/running is a whole body exercise that avoids localized fatigue in lower legs caused by bicycling and (2) walking/running provides a more accurate estimate of the absolute maximal aerobic capacity than any other method (44). A 10° slope is recommended. At each workload (e.g., 3 mph, 4 mph, and 5 mph), heart rate and oxygen consumption are required to stabilize before they are measured. The individual begins with the lightest workload (walking at 3 mph for instance) and performs at that level until steady state heart rate and oxygen uptake values are reached (it usually takes 3 to 4 minutes to reach steady state). These values are recorded. Once the measurements are recorded, the workload is increased to the next higher level (e.g., 4 mph). The procedure is repeated until steady state heart rate and oxygen uptake values at all three workloads are recorded. The recorded heart rate and oxygen consumption values are plotted on an x-y graph (e.g., heart rate on x-axis and oxygen uptake on y-axis) and a straight line is drawn through the plotted points. Next, the value of maximum heart rate for the individual is determined and plotted on the x-axis. There are several formulas that provide the value of an individual's maximum heart rate. The most accurate of these formulas is:

$$\text{Maximum heart rate} = 214 - 0.71 \times \text{Age in years}$$

A vertical line is projected from the maximum heart rate point. A horizontal line is projected from the point of intersection between this vertical line and the straight line joining the three plotted points. The value given by the intersection of the horizontal line and the y-axis is the PWC of the individual.

When the PWC thus determined is compared with the steady state oxygen consumption of a worker on a job, an indication of the physical stress of the job is obtained. If a job requires more than 21% to 23% of PWC for 8-hour shifts, it is very likely to lead to overexertion and, eventually, musculoskeletal problems (9).

Oxygen consumption can be measured by several commercially available devices. All of these devices require the worker to put on a mask, breath room air, and exhale into the mask. The exhaled air is analyzed for oxygen content and compared with oxygen content in the room air to determine average minute oxygen uptake.

Heart rate: When humans engage in work, their cardiovascular system is strained. Heart rate, a frequently measured indicator of physical stress to which the individual is subjected, can be measured directly or indirectly (telemetry). The simplest direct method is to take the pulse once the steady state has been reached. The pulse rate should be recorded for a full minute to avoid the effect of sinus arrhythmia. If the pulse rate is being recorded at the end of the work period, a 15-second sample is sufficient; samples of longer duration tend to project into the recovery period. A 3-minute average at the steady state should be recorded. The maximum working heart rate should not exceed 130 beats/minute.

The other method for recording heart rate is somewhat similar to recording EMG in that active and passive electrodes are used. Two electrodes need to be placed on the rib cage, fairly far apart; the ground is placed on a bony landmark. The skin is lightly abraded if passive electrodes are used; such electrodes are covered with an adhesive collar filled with electrode cream.

Psychophysical Techniques. Psychophysical techniques are suitable for repetitive as well as nonrepetitive (infrequently performed) tasks. While there is still a need for validating some of these techniques with respect to outcomes and measures, such as symptoms of injury, lost time, etc., these techniques are inexpensive and easy to use as there is little or no equipment needed. The techniques described in this section can be used for the lower back as well as the upper extremities, and include measurement of postural discomfort, static and dynamic work (perceived exertion), and fatigue.

Postural discomfort: Extreme postures or postures that are maintained for prolonged periods of time can be uncomfortable, leading to fatigue and pain. It has been determined that the level of discomfort is linearly related to the force exertion time. Maintaining the same posture is physiologically equivalent to applying a force. A body map and a 5-point scale are used to determine the body part discomfort (45). Figure 11 shows both the body map and the scale. The worker experiencing discomfort in the task being investigated specifies the location of discomfort on the chart and rates it using the scale. The worker rates body parts at regular intervals ranging from 30 minutes to 3 hours. It is also advisable to rate the discomfort just before a break. This method is easy to use and reliable results can be obtained.

A general comfort rating scale is another subjective method to assess overall discomfort (46). Initially developed to assess chair comfort, as a significant part of industrial work is done by seated workers, the scale has been found to be reliable for assessing overall body discomfort in a variety of industrial situations. The responses on this scale range from "I feel completely relaxed," to "I feel unbearable pain."

Rating of perceived exertion (RPE): There is a curvilinear relationship between the intensity of a range of stimuli and workers' perception of their intensity. These perceived

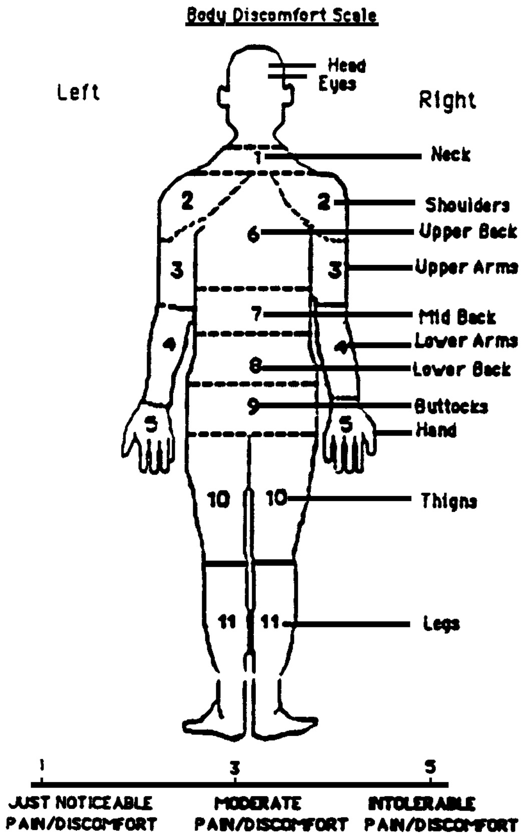

Fig. 11. Body part discomfort form and rating scale (modified from Corlett EN, Bishop RP. A technique for assessing postural discomfort (*Ergonomics* 1976; 19: 175–182)).

exertions can be rated on a Borg Scale (47). The scale steps (6–20) are linearly related to heart rate (heart rate = 10* RPE Scale rating). The scale is presented to the worker before the beginning of work and endpoints (6,20) are thoroughly defined. The scale is then shown to the worker at the end of work and he/she is asked to rate the exertion. A rating of 12 to 13 is desirable as the maximum work intensity that can be sustained without perceived overexertion.

It should be noted that these ratings are influenced by, in addition to the overall perception of exertion, previous experience and motivation. In general, highly motivated subjects tend to underestimate their exertion.

A Borg rating scale with ratio properties to make interindividual comparisons in physical effort ratings (forces/MVC) (48) is also available. This scale is valid only for large muscle groups and should not be used for work performed by fingers and hands.

Other rating scales: A number of other rating scales are available and can be used to elicit information about the job and workplace. One of the techniques employs sharp contrasting pairs of characteristics that give an indication of overexertion or fatigue. The characteristics are:

Fresh	________	Weary
Sleepy	________	Wide-awake
Vigorous	________	Exhausted
Weak	________	Strong
Energetic	________	Apathetic
Dull, indifferent	________	Ready for Action
Interested	________	Bored
Attentive	________	Absent-minded

A 3-, 5-, 7-, or 9-point scale can be used to elicit workers' opinions. An example of a 5-point scale would be a response to a question such as "How do you feel?" at the end of a work period:

1. Fresh	2. Somewhat Fresh	3. Average	4. Tired	5. Weary

In the above scale, each point has a value (1 to 5) depending upon which point is selected. The points for different questions can be added to determine worker's opinion.

A variation in rating technique is represented by Likert's Summated Rating Scale. It is a 5-point scale with which a statement is associated (a number of statements, typically 10–20, are used). An example of this scale is as follows: Statement: "Postural problems are the most serious problems in most of these jobs."

5	4	3	2	1
Strongly agree	Agree	No opinion	Disagree	Strongly disagree

Each scale has a point value (1 to 5). Scores for all statements are added to determine worker's opinion. Similar statements are expected to provide similar scores.

There are many other subjective rating methods, perhaps less easy to use, that are available in the published literature. For a review, refer to Sinclair (49).

SUMMARY

The incidence and costs of occupational injuries in the United States, especially injuries to the back and upper extremities, continue to rise. Rehabilitating injured workers involves application of the principles of disability management. One of the many disciplines involved in such rehabilitation is ergonomics engineering. This paper, in addition to providing the process involved in setting up ergonomics interventions, discusses different risk factors specific to the back and upper extremity musculoskeletal injuries, and provides ergonomic guidelines and recommendations for mitigating the harmful effects of such risk factors.

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