ELSEVIER

Applied Ergonomics 34 (2003) 3–15

APPLIED ERGONOMICS

www.elsevier.com/locate/apergo

Corporate initiatives in ergonomics—an introduction

Göran M. Hägg*

Programme for Ergonomics, National Institute for Working Life, SE-112 79 Stockholm, Sweden

Abstract

Examples in the literature of corporate initiatives in ergonomics are reviewed. Different types of programmes are identified with ambitions ranging from time-limited interventions to continuous processes. Common elements are health surveillance, workstation design and choice of tools, product design, quality aspects, participative aspects and education, training and information. The implementation of ergonomics programmes varies substantially depending on the type of company, and company policies and organisation.

Some of the most developed ergonomics programmes originate from the automobile industry. Other businesses with many established programmes are the electronics industry, the food industry and the office environment. A participative approach, as well as ergonomics expertise, are crucial ingredients for a successful programme. The scientific evaluation of ergonomics programmes, especially in economical terms, is in too many cases insufficient or missing. Furthermore, links to company core values such as quality improvement are often lacking. Programmes in ergonomics are still often seen as solely a matter of health and safety. Only a few companies have reached the state where ergonomics constitutes an integrated part of the overall strategy of the enterprise.

Keywords: Intervention; Participation; Education; Training; Process

1. Introduction

Ergonomics is a fairly new science with its roots in the late 1940s. Over the years the definition of ergonomics has gradually been broadened. Increasing research efforts have yielded a considerable body of knowledge concerning the design of tools and workstations, as well as organisational design to prevent worker discomfort, illness and absenteeism, and also to improve productivity and product quality. The dissemination of this knowledge to working life started early, but for many years these issues were considered mainly as ethical questions handled by the personnel department. The main promoters of ergonomics in industry have traditionally been national authorities such as OSHA in the USA and researchers in the field. During the 1990s the interest for ergonomic issues in a wide sense has grown within enterprises, as a result of an increasing awareness of the importance of these matters for corporate core values such as productivity, quality and an inevitable change process (Wilson, 1999).

One consequence of this is that tailored ergonomic programmes are set up for whole companies or groups within companies, e.g. office workers, floor workshop personnel or designers of products. Such programmes may consist of guidelines concerning aspects of workload, such as work postures and movements, lifts, and also guidelines concerning equipment, product design, noise levels, vibration, lighting, climate, procedural information, safety and work organisation. The company staff is trained to apply good ergonomics to promote health, well being, productivity and product quality. The programme can be a stand-alone ergonomics programme or it can be integrated with other company policies.

Numerous reports in the scientific literature describe such programmes more or less briefly. These reports often concern interventions made by researchers addressing some specific hypothesis. However, the programme documentation is often fragmentary, leaving out information on, e.g. degree of company involvement, long-term impact in the organisation or training efforts.

This paper aims at a critical survey of such company programmes as an introduction to the following technical notes of the present special issue of Applied Ergonomics devoted to the theme "Corporate Initiatives

*Tel.: +46-8-7309314; fax: +46-8-7309246.
E-mail address: goran.hagg@niwl.se (G.M. Hägg).

0003-6870/02/$ - see front matter
PII: S0003-6870(02)00078-9

in Ergonomics". Industrial programmes presented in major international ergonomics journals, conference proceedings and books, mainly over the last decade, have been sought. The inclusion criteria for reviewed programme presentations are that they mainly address physical factors in the workplace and that there is a documented serious involvement by the company. A list of the programmes reviewed in this paper is given in Table 1.

2. Types of initiatives

Company programmes in ergonomics involve a wide range of measures depending on the type of enterprise, company policies and culture, and also national legislation and cultural traditions. They may be initiated by an authority citation (Adler et al., 1997), new legislation (Butler, 2003 this issue), increasing workers' compensation claims or incidence of musculoskeletal disorders (MSD) (Halpern and Dawson, 1997) or demands for a better company image in society or combinations thereof. The initiative may come from the management (Gleaves and Mercurio, 1991; Halpern and Dawson, 1997; Smyth, 2003 this issue), an already existing department for ergonomics or health and safety (Stroud, 1999), external researchers (Axelsson, 2000b; Moore and Garg, 1998) or trade unions (Joseph, this issue). They can basically be characterised either as isolated time-limited actions to solve a specific problem or as continuous processes.

2.1. Time-limited actions

A time-limited action addresses a specific problem at a certain time and hopefully solves the problem; however, it remains an isolated event which often has time-limited consequences in the fast changing working life of today. Many such interventions are initiated by researchers, often with the main purpose of verifying some hypothesis. However, if the addressed problem is acknowledged, and the solution is accepted and implemented by the company, the intervention may be beneficial for the company in addition to the scientific gain.

In contrast to a process described below, a time-limited intervention usually permits before/after measurements, which is rewarding from scientific point of view. Hence, such interventions are likely to be generally overrepresented in scientific reporting of ergonomics measures in the field. For a review, see Westgaard and Winkel (1997).

Another advantage of a time-limited intervention compared with continuous processes is that it is easier to evaluate from an economical point of view as an investment yielding a possible profit. For a survey of such measures, see Oxenburgh (1991).

2.2. Continuous processes

Changes in modern enterprises are increasingly described as continuous processes. 'Continuous improvements' is a basic, originally Japanese concept, which has inspired large parts of the industrial world (Lillrank and Kano, 1989). In line with this, ergonomics programmes are set up as continuous processes, involving the whole enterprise or major parts of it (e.g. (Joseph, this issue; Smyth, 2003 this issue)). In the fast changing industrial world such an approach is inevitable in a longer perspective, since single interventions soon loose their relevance. At the start of a continuous ergonomics process the major activities are often of a reactive nature. If the programme is sound it will mature; it will gradually involve more proactive measures and become an integral part of the company's policy (e.g. (Albin, 1999; Gleaves and Mercurio, 1991; Munck-Ulfsfält et al., 2003 this issue).

3. Elements of ergonomics programmes

When examining corporate ergonomics initiatives, a number of basic elements may be discerned, as briefly described and exemplified below.

3.1. Workstation design and choice of tools

There is a comparatively large amount of knowledge available regarding optimal design of workstations and tools, acceptable workloads and related risk factors. Even if definite limits still do not exist in many cases, there is a good basis for the identification of definitely adverse conditions (Hagberg et al., 1995). Hence, today it is meaningful to operationalise this knowledge into workplace assessment systems, e.g. by three-class gradings, green/yellow/red, where green stands for acceptable, yellow for possibly acceptable (further assessment needed) and red for unacceptable (e.g. NBOSH, 1998). Such classification systems and checklists have been tailored for different company needs and used at different kinds of audits, and also in the design process (Herring and Wick, 1998; Jimmerson, 1998; Moreau, 2003 this issue; Smyth, 2003 this issue; Svensson and Sandström, 1995).

The design of hand-held tools has lately improved considerably in terms of ergonomics. However, there are many (often cheaper) less suitable tools available on the market and the choice is not easy. Therefore, some companies have established special committees with representatives from the departments for engineering, purchasing, production and ergonomics to assess and test tools on the market (e.g. Munck-Ulfsfält et al., 2003 this issue). All purchased tools have to be approved by the committee.

Table 1
Reviewed programmes

Type of business	References	Basic contents	Outcome/evaluation	Comments
Automotive industry	Brandenburg and Bubser (1999)	Health surveillance. Health dpt. involved in audits, reactively as well as proactively	Reduced costs due to improved health	No connection between health surveillance and quality programme
	Klatte et al. (1997)	Quality improvement through ergonomic workstation design		
	Joseph (this issue)[a] Joseph and Long (1991) Jimmerson (1998) Kilduff (1998) Siffer and Jimmerson (2000)	Ergonomics process involving reactive and proactive measures. Training programme. Dissemination to plants in other countries	Reduced number of worker compensation claims	
	Moreau 2003 (This issue)[a]	Development and application of ergonomics assessment tools Health surveillance	Reduced MSD incidence	
	Munck-Ulfsfält et al. 2003 (This issue)[a]	Ergonomics process involving reactive and proactive measures. Training of all personnel. Integral part of quality strategy	Increased ergonomics awareness on all levels	
	Oriet and Ewasyshyn (1998)	Traditional ergonomics programme	?	Documentation sparse
	Stroud (1999) Svensson and Sandström (1995) Svensson and Sandström (1997)	Ergonomics process involving reactive and proactive measures. Training programme Feedback of MSD per department with estimated costs	?	
	Sugimoto et al. (1998)	Assessment model to match workstation design to worker capacity	Reduced physical strain	
Beverage distribution	Bugge and Berger (1994)	Change of manual handling routines and equipment in the distribution chain	Improved working conditions according to questionnaire among distribution personnel	Initiatives adopted by competitors
	Butler 2003 (This issue)[a]	Change of manual handling routines and equipment in the distribution chain	Reduced costs due to decreased worker compensation claims. Profitable investments	
Cosmetics manufact.	Smyth 2003 (This issue)[a]	Training of engineers and operator representatives in all departments. Health surveillance with direct feedback to departments	Reduced MSD incidence	
Electrical installation	Niggebrugge and Schelle (1999)	Information campaign on posters, brochures and mouse pads	?	Documentation sparse
Electronics industry	Aarås (1999) Aarås (1994)	Workstation design	Reduced MSD incidence Reduced costs due to reduced staff turnover, recruitment and sick leave. Profitable investments	
	Chatterjee (1992)	Improved tools and workstations. Workforce training	Reduced MSD incidence	
	Helander and Burri (1995)	Extensive traditional ergonomic measures. Training of personnel. Information on videos and brochures. Travelling exhibition	Reduced costs due to productivity increase, improved quality and injury reduction. Profitable investments	Four plant cases in detail
	Herring and Wick (1998)	Observation and checklist tools to identify adverse workstations	Reduced MSD incidence	
	McKenzie et al. (1985)	Extensive traditional ergonomic measures. Training of engineers and supervisors	Reduced MSD incidence	
Hearing protection manufacturing	Odenrick and Arvidsson (2000)	Expert-supported participatory change groups addressing workstation design and work organisation	Several improvements regarding workstations and organisational design	
Lighting manuf.	Gleaves and Mercurio (1991)	"Ergonomic circles" at each department responsible for problem identification and solving. Ergonomics training for all hourly workers	Several workstation improvements. Generally better team spirit	

Table 1 (*continued*)

Type of business	References	Basic contents	Outcome/evaluation	Comments
Office	Aarås (1999) Aarås et al. (1998)	Improved lighting, furniture and individually adapted glasses	Reduced visual discomfort and pain	
	Albin (1999) Albin et al. (1997)	Group training, furniture and equipment specifications. Self-help software. Office ergonomics clinic with advice to workers with problems	Profitable investment in equipment due to reduced worker compensation claims. Change in company culture	
	Baxter and Harrison (2000)	Training programme for local "ergonomics expert" operators	Reduced costs due to decreased worker compensation claims and lost time. Profitable investment	
	Robertson et al. (2000)	Ergonomics training for supervisors and workers. New office equipment "Video kiosk" information. Mock-up demonstrations	Reduced MSD. Increased knowledge and user control	Three case reports
Railway car repair	Laitinen et al. (1998)	Participatory process to improve workstations, tools and procedures	Reduced absenteeism. Less MSD incidence. Improved psychosocial climate	
Red meat industry	Gjessing et al. (1994) Moore and Garg (1998)	Participatory process to improve workstations, tools and procedures	Reduced costs due to decreased worker compensation claims and lost time.	
	Smith (1994)	Training of supervisors and employees in ergonomics. Employees as ergonomics coordinators. Employee focus groups	Mainly decreased MSD incidence	
Sewing	Halpern and Dawson (1997)	Expert-supported change groups to improve workstations, tools and procedures	Reduced costs due to decreased worker compensation claims	Initially increasing MSD rates
Telecommunications	Baxter and Harrison (1998)	Union/management human factors work group, providing information, audits and problem solutions	Reduced MSD incidence	
Unspecified assembly work	Axelsson (2000a)	Participatory self-assessment of working postures (RULA)	Improved quality and reduced MSD incidence	

[a] In this issue.

3.2. Product design

The design of a product is essential for the working conditions when producing it, influencing the load on the workers as well as production costs and quality outcome (Helander and Nagamichi, 1992). The more complex the work that has to be done on a product, the more important these aspects become. Hence, product design is addressed in many company programmes for ergonomics. This concept has been developed mainly in the automobile industry (e.g. Munck-Ulfsfält et al., 2003 this issue; Svensson and Sandström, 1997). However, attempts have also been reported from the electro-mechanical industry (Broberg, 1997).

Components delivered by subcontractors often cause ergonomic problems in assembly work. Hence, demands are also put on such components, e.g. fasteners (Munck-Ulfsfält et al., 2003 this issue). Furthermore, work is reported regarding the development of ergonomic guidelines for electrical connectors, intended for sub-contractors. Mechanical properties are crucial for assembly strain, as well as for connection quality, and hence they become an issue of product quality (Siffer and Jimmerson, 2000).

3.3. Organisational design

Work organisation is an important part of the modern broad ergonomics concept. In particular, the opportunities for job variation, rotation and enlargement are of great importance for the prevention of MSD. There is an extensive literature regarding industrial organisation, but there are few examples where organisational issues are addressed in conjunction with more traditional ergonomics issues. However, the Volvo Car Corporation (VCC) touches upon these issues in their programme presented in this issue (Munck-Ulfsfält et al., 2003 this issue).

3.4. Quality aspects

Quality improvement of products and services has been a major incentive for the development of industrial production in the industrialised world for several decades. A major point is that poor working conditions are related to quality deficiencies and vice versa. Thus, improved ergonomics is one way of achieving better quality, and there is today strong scientific support for such a view (Eklund, 1997) and an increasing awareness in industry of these relationships (Wilson, 1999). However, when reviewing the present documentation of company programmes in ergonomics, there are few explicitly declared links between ergonomics and quality policies. One example, from the automobile industry is the VCC KLE strategy (KLE Swedish acronym for Quality, Delivery and Economy) (Munck-Ulfsfält et al., 2003 this issue), where the ergonomics programme is an integral part of the quality strategy. At Volkswagen (VW) the relation between quality and ergonomics is acknowledged and applied in a process-audit programme for production development (Klatte et al., 1997). Axelsson (2000b) describes an intervention at an assembly line where the aims are twofold: improved quality and improved working conditions. These goals are reached by a participative process.

3.5. Participative aspects

The participation of the employees on all levels in the development of the work and its environment is another important concept in modern ergonomics (Noro and Imada, 1991). The worker is supposed to be an expert in what he/she is doing the whole day. These thoughts are closely kindred with Japanese management philosophies like "kaizen" (Imai, 1986) which are also cornerstones in the quality movement. During the last decade, the necessity of a participatory approach has evolved into a truism in ergonomics. Hence, in almost all reviewed programmes it is stated that staff representatives from all levels act in various committees, involved in reactive as well as proactive work. Most investigators agree that a participatory approach is essential for the success of an ergonomics programme. However, an example, which illustrates that participation alone does not necessarily imply good ergonomics, is the NUMMI case (Adler et al., 1997). In spite of a participatory approach according to the Toyota production philosophy, severe musculoskeletal problems developed, leading to an OSHA citation. One reason for the problems was that the knowledge of ergonomics within the company was poor (Adler et al., 1997).

One way of developing the participatory approach is to provide the operators with simple methods for self-assessment of the working conditions. An example of this is where the RULA method (McAtamney and Corlett, 1993) was taught and applied by assembly operators as a basis for ergonomic changes at the workplace (Axelsson, 2000b). Video-based methods, VIDAR and PSIDAR, addressing physical and psychosocial factors, respectively, have been developed for similar purposes (Johansson Hanse and Forsman, 2001; Kadefors and Forsman, 2000). Another example of a genuine participative process is the change of assembly work, performed by the workers themselves, which is supported by external researchers (Odenrick and Arvidsson, 2000). This project is described in more detail below.

3.6. Health surveillance

Good health among the staff is a basic objective in ergonomics. Medical health care directly provided by the employer is common in many large corporations (e.g. Brandenburg and Bubser, 1999; Stroud, 1999). Apart from being an employee benefit, it may provide an excellent tool for identifying problematic workstations and tasks (Hagberg et al., 1997; Smyth, 2003 this issue). Prerequisites for the efficacy of such a function are that the health care personnel are specially trained to identify a possible relationship between a disorder and the actual work conditions, and that they have direct feedback channels to company management on appropriate levels, in order to initiate appropriate action. Detailed health care statistics on workstation level, combined with price tags for the average rehabilitation costs of common diagnoses, as applied at SAAB Automobile, may highlight problem areas and their economical consequences, and serve as an incentive for management to change the conditions (Stroud, 1999).

Another tool for the identification of health problems is active screening of the health of the workforce by different kinds of questionnaires (Kilbom, 1995; Smyth, 2003 this issue). According to Swedish and Norwegian law, some sort of surveillance system of this kind is mandatory for all enterprises (Systematic Work Environment Management) (SWEA, 2001). This law stimulates the establishment of ergonomics programmes.

3.7. Training and information

A key issue when implementing an ergonomics programme in an enterprise is the training of the staff. In several programmes, the training efforts have been declared in more or less detail, aiming at various staff groups. For example, in the Volvo programme all levels, from top management to shop floor staff, receive tailored training programmes (Munck-Ulfsfält et al., 2003 this issue). Design and production engineers are trained to use checklists in their daily activities, which is also the case at SAAB (Svensson and Sandström, 1995, 1997). The Boots Contract Manufacturing Programme has 2 days of training for "ergonomics champions", with one staff representative from each department (Smyth, 2003 this issue), and some other programmes show similar solutions (Baxter and Harrison, 2000;

Munck-Ulfsfält et al., 2003 this issue). Another way of distributing information is by instruction videos (Moreau, 2003 this issue; Robertson et al., 2000). The GTI company in the Netherlands chose an unconventional approach, basing an information campaign in ergonomics on two popular cartoon characters who appeared on posters, hand-outs and mouse pads (Niggebrugge and Schelle, 1999). In large multinational corporations, the availability of ergonomics information is assured via Intranet systems (Evans et al., 2000; Oriet and Ewasyshyn, 1998).

Another aspect of training is when individuals are trained to adopt a favourable work technique. This can be done just by observation and instruction by an ergonomist or by a senior staff member, specially trained for this function (Munck-Ulfsfält et al., 2003 this issue; Smyth, 2003 this issue). Another possibility is to use electromyographic feedback technique for training of minimal muscle exertion (Hägg, 1998). This approach was effectively used by Parenmark et al. (1988) at a chain saw plant, and the technique was still in use in 1999 as a company routine (Hafström, 1999, personal communication).

4. Implementation

The organisational implementation of ergonomics programmes varies substantially, depending on the type of company and company policies and organisation, as described in the presentations of this issue and other given examples. Most commonly, the operational responsibility for these programmes lies with the departments for occupational health and safety or on the ergonomics department if there is one. Usually, one or several ergonomics committees (depending on the size of the company and the number of plants) are founded. A common pattern is that a central committee has the overall responsibility for the activities, while the operational responsibility is taken on by local committees (e.g. (Baxter and Harrison, 1998; Gleaves and Mercurio, 1991; Joseph, 2003). These working committees normally consist not only of ergonomists but also of representatives from production and design engineering, production supervisors and shop floor personnel.

At the start, the activities usually have to be limited to reactive measures, but if the programme is successful and is given reasonable resources to be established as a continuous process, the activities are expanded to involve proactive efforts as well. When investing in new production facilities or new products, proactive input to the change process is of vital importance for a future operation with higher quality, less health problems and greater satisfaction.

Even if the proactive efforts are developed to an excellent level, it is important to preserve a continuous reactive readiness (see e.g. Smyth, 2003 this issue). Problems are likely to emerge, even in the best designed production process.

5. Examples of programmes from different business areas

5.1. The automotive industry

The automotive industry has been claimed to be "the industry of industries" (Womack et al., 1990). Hence, the world's largest manufacturing industry is a pioneer in many aspects of industrial development, and ergonomics is no exception. Car manufacturing involves many classical ergonomic risk factors such as repetitive work, awkward postures and hand-intensive work. Hence, the need for ergonomic considerations is obvious. Consequently, some of the most well-established ergonomics programmes reviewed in this paper originate from the automobile industry.

The UAW/Ford manual, which was developed in cooperation with the University of Michigan (Joseph and Long, 1991), constitutes the basis for the Ford process of today, involving reactive as well as proactive measures (Joseph, 2003). The proactive activities address workstation as well as product design. Being one of the major car manufacturers with plants all over the world, efforts have been made to transfer the basic concept to other continents by translations and adaptations to local conditions. Ford also carries out applied research in-house (e.g. Stephens and Vitek, 1998).

More specific guidelines for design and production engineers have been developed at SAAB Automobile (Svensson and Sandström, 1995, 1997), which also has a developed process (Stroud, 1999). Similar work is going on within the General Motors Corporation (which owns SAAB) to achieve a global corporate standard in ergonomics (Stroud, 1999, personal communication). At present, detailed technical guidelines addressing physical factors are available (GM, 2000) but there is no description of the implementation process, training efforts, etc.

The third big manufacturer in the USA, the Chrysler Corporation, also applies its own ergonomics programme (Oriet and Ewasyshyn, 1998). This programme includes traditional elements and has been established for a couple of years. However, the available documentation is sparse.

VCC has developed an extensive programme and process, with all the traditional elements, as referred to above (Munck-Ulfsfält et al., 2003 this issue). The process is an integral part of the quality philosophy (see above). VCC was purchased by Ford in 1999.

Recently, the since long established health care and ergonomics contractor, which to a large extent has been responsible for the development of the ergonomics programmes at VCC (Munck-Ulfsfält et al., 2003 this issue), has been exchanged for another contractor with little experience from the vehicle businesses (Munck-Ulfsfält, 2002, personal communication).

In Germany, VW has an extensive programme in health surveillance (Brandenburg and Bubser, 1999). The health care staff are also involved in ergonomic audits, as well as in the development process of new production units. The company also applies quality development through improved ergonomics (Klatte et al., 1997). However, these programmes seem to have no connection. Mercedes-Benz has developed a system for assembly production planning, which also takes ergonomics into account (Bullinger et al., 1997). However, it is not known whether this system is applied generally within the company or what other initiatives in ergonomics are taken.

For the last couple of years, the Rover Group in Great Britain has been developing an ergonomic process partly based on a self-assessment method (ABA, German acronym for Associate Job Assessment) from their former German owner BMW, and also with development support from the University of Loughborough (Piotrowski, 2000). Peugeot in France is also venturing into an ergonomics programme initiated from their health department (Moreau, 2003 this issue). This programme mainly focuses on MSD prevention through the development and application of ergonomic assessment tools for reactive as well as proactive measures.

Even if major trends in production planning and organisation have originated in Japan during the last few decades (e.g. kaizen and lean production), Japanese reports of ergonomics programmes in the Euro-American sense are sparse. Toyota reports about a programme avoiding back pain when remodelling assembly lines (Sugimoto et al., 1998). However, the case report about the Toyota transplant, NUMMI, in California indicates deficiencies regarding traditional ergonomics (Adler et al., 1997).

5.2. The electronics industry

The electronics and computer industry has grown enormously since the Second World War. In spite of great progress in the automation of manufacturing, many tasks still require manual handling of different kinds, often at high repetitivity rates. At the same time, many new surveillance tasks requiring advanced technical knowledge have appeared. Thus, programmes in ergonomics are needed in this sector.

One of the major companies, IBM, has for several decades applied ergonomics in production, and the activities have slowly matured, becoming an integrated part of the business during the 1990s (Helander and Burri, 1995). The programme incorporates all the elements discussed above. In the paper, four case studies from different plants are described in addition to the ergonomics process. The measures are also evaluated economically and indicate substantial profits.

In a study of a telecommunications manufacturing plant, a positive effect on MSD was obtained by a change of tools, and training in ergonomics of engineers and supervisors (McKenzie et al., 1985). Another successful intervention project addressing traditional ergonomics issues such as vibration levels, seating, postures and static loads, workforce training and health surveillance yielded a positive effect on MSD problems in an electromechanical plant over a period of 8 years (Chatterjee, 1992). Similar results were obtained by applying an observation technique and checklists (Herring and Wick, 1998).

Aarås and colleagues have long-term experience of introducing ergonomics at a company that manufactures telecommunication equipment (Aarås and Westgaard, 1980; Aarås, 1999). The main focus of the programme is the reduction of MSD through changes of workstation design in electronics assembly (Aarås, 1994). The programme has been evaluated regarding the occurrence of MSD, and also in economical terms. As a result of substantial reduction in staff turnover and sick leave, the investments in better ergonomics were demonstrated to be highly profitable.

5.3. The food industry

Within the food industry numerous adverse ergonomic factors are found. Especially in slaughterhouses and poultry industries, high repetitivity rates, high manual forces, awkward postures, and a cool environment create large problems. Hence, these businesses have appeared among the highest figures of MSD in official statistics for decades (e.g. NBOSH, 1999). Solving the disorder problems avoiding worker compensation claims are the main incentives, while quality issues are less emphasised.

The problems in the red meat industry in the USA caused NIOSH to launch three intervention studies at three plants (Gjessing et al., 1994). One of these studies is also published and described separately (Moore and Garg, 1998). These studies were all supervised by an external expert in ergonomics or organisational behaviour. The summarised conclusions strongly advocate participatory approaches, involving staff members on all levels, i.e. engineers, supervisors, and operators in teams for ergonomic problem-solving. Other crucial prerequisites were training in ergonomics and team building for all participants, as well as support from ergonomics expertise and management. Experience from the implementation of another programme in the red meat industry was very much the same (Smith, 1994).

5.4. Transportation

Local distribution of goods by lorries and vans includes loading/unloading under varying conditions, which are often not controlled by the distributing company but by the customer. These circumstances often imply unacceptable conditions for the workers. For example, at the Scottish brewery Scottish & Newcastle (S&N) a majority of the draymen required early retirement due to MSD (Butler, 2003 this issue). Two main lines of approach were chosen. Firstly, vehicles, containers and transport procedures were assessed from an ergonomic point of view, and several improvements were implemented. Secondly, the cellars of the customers were inspected, and minimum requirements regarding physical accessibility were set and implemented. This latter problem is somewhat simplified, since S&N owns many of the pubs and restaurants where the deliveries are made. Similar problems in the Norwegian brewery Ringnes were solved in very much the same way (Bugge and Berger, 1994). The measures were evaluated economically and found profitable. The positive outcome has led to the formation of a Norwegian network (LUKS), involving other beverage and food distributors who apply the same kind of solutions. In Sweden, these problems are addressed in a national project (Maximum five steps), where the Swedish Brewery Association is one of the participants (Ros, 1999).

5.5. The office sector

Today the ergonomics of office work is linked to a considerable extent to the fast development of information technology. The use of computers is associated with numerous MSD (Punnett and Bergqvist, 1997). Sight problems associated with VDUs are also common.

Aarås and colleagues have addressed these issues in a telecommunications company by company standards for office lighting and furniture, VDU placement and an individual optometric investigation with free special spectacles to be used at work (Aarås, 1999; Aarås et al., 1998).

Another approach is described by Albin and colleagues who have started "office ergonomic clinics", where employees with MSD receive medical treatment but are also advised regarding computer ergonomics at a demonstration workstation (Albin, 1999; Albin et al., 1997). Yet another approach is described by Butler 2003 (this issue), who has developed a display screen equipment programme as a part of a larger programme.

Baxter and Harrison (2000) describe a programme where selected operators from different telephone operator offices were trained for 2 days in basic office and computer ergonomics. These operators serve as "local experts" in their departments and teach ergonomics to their fellow workers. This programme has been evaluated economically, and indicates substantial savings.

In three described cases, different variants of office ergonomics programmes in three companies are reported (Robertson et al., 2000). The training of the employees regarding office ergonomics in general and handling of personal adjustable equipment are emphasised as key elements in the programmes.

5.6. Miscellaneous

A large enterprise making mainly cosmetics and healthcare products initiated an ergonomics programme by employing a full-time ergonomist (Smyth, 2003 this issue). In the paper, the progress after 2 years is reported. The programme includes ergonomic considerations when developing new equipment and processes, training of "ergonomic champions" among the operators within each department, learning proper working techniques and continuous health surveillance. The immediate identification of early MSD and corresponding problem-solving is especially stressed.

Machine-sewing work is associated with static, sometimes awkward, postures. Hence MSD among professional sewers are common (Schibye et al., 1995). An ergonomics programme in a sewing industry was introduced by Halpern and Dawson (1997). The programme involved several improvements of the workstation and tools, organisation and also a structured resting and stretching schedule on a participatory basis. The approach involved expert-supported change groups with representatives for all staff categories. Risky work situations were identified by the experts; they also suggested changes to the change groups, who modified the suggestions before final implementation. One example of measures is the conversion from sitting to standing workstations. Another is the introduction of rest and stretch schedules. The programme resulted in substantially reduced MSD problems over a 5-year period.

Baxter and Harrison (1998) describe the enforcement of ergonomics at BC TEL (telephone company in British Columbia, Canada) via a strong Human Factors Working Group, consisting of both union members and management members. This group is provided with the resources and the authority to carry out ergonomic changes and training in all areas and levels of the organisation.

MSD problems and high absenteeism characterised a railway repair plant in Finland. A programme addressing procedures, tools and materials handling on a participatory basis improved the situation significantly by creating a better psychosocial climate, reducing absenteeism and MSD (Laitinen et al., 1998).

Another example where MSD problems initiated the development of an ergonomics programme is reported from a lighting manufacturing company (Gleaves and Mercurio, 1991). At the heart of the programme are ergonomic circles formed at each department, with representatives from all staff categories. The ergonomics work is centrally coordinated by a steering committee. These circles have come up with solutions to simple ergonomic problems as well as proactive work at new investments. The investigators also emphasise the improved collaboration between workers and management.

In order to reduce the repetitivity of manual assembly work in a company making hearing protection devices, a change process was initiated (Odenrick and Arvidsson, 2000). This case is an example of how external ergonomics experts provide documentation of the prevailing situation as a basis for an improvement process based on the operators' own experience and ideas. Teams of operators were formed, supported by the researchers, and solutions concerning how to design the new workstations, as well as how to change the work organisation, were developed by the teams.

In a venture to improve working conditions as well as production quality in a company with unspecified assembly work, positive results were reported regarding MSD as well as quality (Axelsson, 2000b). The approach was based on participative self-assessment, applying the RULA method (McAtamney and Corlett, 1993).

6. Discussion

The programmes reviewed in this paper are the ones that happen to be reported in scientific literature. These programmes most likely constitute only a fraction of all ergonomics programmes and processes in operation all over the world. Furthermore, the selection of available reports is a difficult matter. There are, for instance, a large number of field interventions reported by researchers, where the involvement of the company is doubtful. The chosen reports are considered to have genuine company support; however, in many cases this is hard to assess. To my knowledge, only two reviewed programmes have a representative from top management as a co-author (Munck-Ulfsfält et al., 2003 this issue; Oriet and Ewasyshyn, 1998).

The scientific quality and wealth of detail in the reports varies considerably. Many of them are mainly descriptive with little or no evaluation and critical discussion. This is understandable when the author is a company representative who may not have an appropriate scientific training or, even if he/she has, cannot express criticism due to loyalty with the company or ventures. Only a restricted number of programmes in this review have been evaluated by unbiased external researchers (Axelsson, 2000b; Helander and Burri, 1995; Laitinen et al., 1998; McKenzie et al., 1985; Moore and Garg, 1998). It is hard to critically assess the general structure a company programme is based on, often meagre, from reports written by people involved in the activities. Few general directives can be given regarding an optimal programme for a given company, since this depends on a large variety of local factors, such as the type of enterprise, company culture, national legislation and traditions.

One conclusion is that more research, performed by external independent researchers, is needed to critically evaluate corporate initiatives in ergonomics. However, this does not imply that other reports are of no value. The fact that they have been carried out and reported must signify that most of them are likely to add value to the company. Furthermore, the assembled documentation provides a picture of the state of the art regarding the practical application of ergonomics, and can serve as a reference for practitioners considering venturing into similar programmes.

Yet another problem is that all reports, including the scientifically good ones, are success stories. It is most likely that there are also programmes which have failed, and, maybe even more interesting, programmes that were never started due to resistance from the management. It would be most valuable to also have such cases reported, so as to be able to learn from the mistakes of others and to learn what hindrances there are for the introduction of ergonomics in working life.

A good question is: What parameters should be addressed in an evaluation of an ergonomics programme? The ultimate parameter from the management point of view is, of course, the profitability of an investment in ergonomics. Some investigators carry out such estimations (Aarås, 1994; Albin, 1999; Baxter and Harrison, 2000; Bugge and Berger, 1994; Butler, 2003 this issue; Helander and Burri, 1995), while others limit their economical evaluation to an estimation of the reduced costs (Brandenburg and Bubser, 1999; Halpern and Dawson, 1997; Moore and Garg, 1998). A conclusion is that ergonomics programmes should to a greater extent be fully economically evaluated in accordance with suggested methods and given examples (e.g. Oxenburgh, 1991, 1997) in order to demonstrate the economical value of such investments.

A large number of programmes are evaluated in terms of MSD incidence and/or worker compensation claims (see Table 1), which is most likely equal to reduced costs. This mirrors the fact that most programmes are driven by health and safety professionals and ergonomists, whose main concern is the health and safety of the employees. In many cases, this seems to be a sufficient motive for sustaining a programme: "The protection and promotion of the employees' health are at VW above all a humanitarian and social obligation" (Brandenburg and Bubser, 1999). "One of VCC's core values is environmental care" (Munck-Ulfsfält et al., 2003 this issue). Aarås states that a scientific evaluation of the effects on the workers' health and comfort caused by the measures taken in ergonomics is essential for management approval at his company (Aarås, 1999). A company policy of this kind is unfortunately too rare.

In several evaluations of the effects on MSD, the claimed improvements may be caused by other courses of events within the company or the surrounding society. A demonstration of contrasts in the outcome in relation to suitable reference groups within and/or outside the company strongly supports a claimed improvement. Such comparisons are rarely seen. The possibility of a "Hawthorne effect" should be considered. Initial positive overreactions due to the measures taken are likely to be common. Opposite effects can also be seen. Increasing the ergonomic awareness in an organisation may also stimulate workers to report disorders that were previously not regarded as work related (Halpern and Dawson, 1997, Moore and Garg, 1998).

Yet another common outcome of a company programme in ergonomics is the impact on company culture and psychosocial climate (Albin, 1999; Gleaves and Mercurio, 1991; Laitinen et al., 1998). These effects are hard to quantify but are most likely of great importance for a company in that they increase the commitment of the employees.

As stated above, a participative approach has become more or less mandatory in ergonomics today, and almost all programmes include such elements. However, it is hard to know, based on the present documentation, to what extent the programmes live up to such declarations in practice. Own experience from Sweden indicates that declarations regarding participation may easily be overlooked, for example when the change process needs to be speeded up (Fredriksson et al., 2001).

In several programmes, it is stated in general terms that working conditions are important for product quality. However, with three exceptions (Axelsson, 2000b; Klatte et al., 1997; Munck-Ulfsfält et al., 2003 this issue), these declarations are not substantiated any further. In spite of a strong focus on quality issues today, especially in the automotive industry, the connection between programmes mainly addressing physical factors reviewed here and quality programmes is weak. In the publication from VW regarding health and safety, quality is mentioned once in a subordinate clause (Brandenburg and Bubser, 1999), while there is obviously a parallel programme within the company focusing on ergonomics and quality issues (Klatte et al., 1997). The workstation assessment tool used by Toyota (Sugimoto et al., 1998) seems to be applied in parallel with and independent of continuous improvement and quality management programmes. It has recently been claimed that up to 50 per cent of quality problems in the manufacturing industry are due to a bad work environment (Axelsson, 2000a). From this perspective much remains to be done regarding the integration of quality and ergonomics programmes. However, in this context it should be noted that while the link between operator performance and product quality is strong for instance in the automotive industry, it is much weaker in other businesses such as the red meat industry (Moore and Garg, 1998), beverage distribution (Butler, 2003 this issue) or the cosmetics industry (Smyth, 2003 this issue).

It has already been concluded that increased researcher involvement is desirable for critical evaluation. Another aspect of this is that researchers can provide expert input to the process. However, the role as expert must be strictly separated from the role as evaluator. It may be claimed that the well-established programmes at, e.g. Ford and VCC are, to a considerable extent, results of the long-lasting symbiotic collaboration with local research institutions. The value of researcher involvement is also emphasised in the Rover presentation (Piotrowski, 2000). Several other programmes rely on external researcher support (Axelsson, 2000b; Laitinen et al., 1998; Moore and Garg, 1998; Odenrick and Arvidsson, 2000). If expertise is not provided by researchers, it should be assured from consultants or hired professional ergonomists. Lack of expertise may jeopardize serious intentions, as shown in the NUMMI case (Adler et al., 1997).

Ergonomics can be introduced in various ways, ranging from bringing in consultants to solve single problems, to the incorporation of ergonomics in the overall strategy of the company. Unfortunately, many companies still consider ergonomics as a health and safety issue only, and have not realised the potential of ergonomics for the development of the total efficiency of the company (Porter, 1998). Hopefully, more and more enterprises realise this potential as, e.g. described in the KLE strategy at VCC (Munck-Ulfsfält et al., 2003 this issue). In most cases, this is a maturation process which must take time (Albin, 1999).

In recent years, emphasis has been given to the role of variation and duration aspects of the workload to avoid MSD (Winkel and Mathiassen, 1994). Rotation between workstations is recommended in general terms in several programmes, but it is remarkable that working hours, breaks, job rotation, etc. are rarely addressed. Generally, the connection between work organisation and adverse physical exposure has been overlooked. In the Ford programme presented in this issue, it is clearly stated that "Ford's primary control strategy is to use engineering controls" (Joseph, 2003). However, the next sentence declares that "the most effective controls often involve a combination of both engineering and administrative controls".

In the presentation from Peugeot in the present issue, these conditions are clearly illustrated by the increase of the MSD incidence rate when the cycle time on the assembly line was drastically reduced, in spite of substantial measures to improve traditional ergonomic conditions such as heavy lifts and awkward postures (Moreau, 2003 this issue). Own experience shows very much the same reactions when introducing an assembly line with improved postures instead of off-line workstations (Fredriksson et al., 2001). Moreau is aware of these shortcomings in the present ergonomic assessment tools at Peugeot. Thus, in companies where there are monotonous, repetitive work tasks, e.g. in car manufacturing, electronics assembly work, or meatpacking, a much clearer focus on organisational issues is needed to achieve an improvement of working conditions.

Conclusions

- Corporate initiatives in ergonomics are important for productivity, quality and staff well being in many enterprises.
- A participative approach is a basic prerequisite for the success of a programme.
- Expertise in ergonomics, external or internal, is also essential.
- More research should be carried out regarding the effectiveness of such programmes.
- There are few examples where quality and ergonomics programmes are integrated.
- A majority of the programmes reviewed are mainly considered as a health and safety issue. Much work remains to be done in order to achieve an integration of ergonomics and general company policies.
- There should be a clearer focus on organisational issues such as job rotation and working times.

References

Aarås, A., 1994. The impact of ergonomic intervention on individual health and corporate prosperity in a telecommunications environment. Ergonomics 37, 1679–1696.

Aarås, A., 1999. Experience from co-operation in ergonomics during a 25 year period. In: Wikström, B.O., Hägg, G.M. (Eds.) Corporate Initiatives in Ergonomics, Arbete & Hälsa 1999:10, NIWL, Stockholm, pp. 86–91.

Aarås, A., Westgaard, R.H., 1980. The organisation and execution of work environmental projects in a Norwegian industrial company. Ergonomics 23, 707–726.

Aarås, A., Horgen, G., Bjørset, H.-H., Ro, O., Thoresen, M., 1998. Musculoskeletal, visual and psychosocial stress in VDU operators before and after multidisciplinary ergonomic interventions. Appl. Ergon. 29, 335–354.

Adler, P., Goldoftas, B., Levine, D., 1997. Ergonomics, employee involvement and the Toyota production system: a case study of NUMMI's 1993 model introduction. Ind. Labor. Relat. Rev. 50, 416–437.

Albin, T., 1999. Maturation and development of the ergonomics process within a large, multinational corporation. In: Wikström, B., Hägg, G. (Eds.), Corporate Initiatives in Ergonomics, Arbete & Hälsa 1999:10, NIWL, Stockholm, pp. 92–95.

Albin, T., Hebaus, M., Ley, C., 1997. Office-ergonomics clinic results at thirty months. J. Occup. Environ. Med. 39, 1031.

Axelsson, J.R.C., 2000a. Quality and ergonomics. Towards successful integration. Doctoral Thesis, University of Linköping.

Axelsson, J.R.C., 2000b. 'RULA in action building the SIMPLE framework for integrated quality and ergonomics improvements' in Quality and ergonomics. Towards successful integration. Doctoral Thesis, University of Linköping, pp. 211–248.

Baxter, K., Harrison, D., 1998. Spreading out the workload: Ergonomics by committee. In: Kumar, S. (Ed.), Advances in Occupational Ergonomics and Safety, Vol. 2. IOS Press, Amsterdam, pp. 127–130.

Baxter, K., Harrison, D., 2000. A simple cost benefit analysis for an ergonomics "train-the-trainer" program. In: IEA-2000, Vol. 2. HFES, San Diego, pp. 1–3.

Brandenburg, U., Bubser, R., 1999. Health management at VOLKSWAGEN. In: Wikström, B.O., Hägg, G.M. (Eds.), Corporate Initiatives in Ergonomics, Arbete & Hälsa 1999:10, NIWL, Stockholm, pp. 62–68.

Broberg, O., 1997. Integrating ergonomics into the product development process. Int. J. Ind. Ergon. 19, 317–327.

Bugge, S., Berger, J., 1994. Bridging the gap between ergonomical knowledge, work design and organisation. In: McFadden, S., Innes, L., Hill, M. (Eds.), IEA-94, Vol. 6, HFAC, Toronto, pp. 56–59.

Bullinger, H., Rally, P., Schipfer, J., 1997. Some aspects of ergonomics in assembly planning. Int. J. Ind. Ergon. 20, 389–397.

Butler, M., 2003. Corporate ergonomics programme at Scottish & Newcastle. Appl. Ergon. 34 (1), 35–38.

Chatterjee, D., 1992. Workplace upper limb disorders: a prospective study with intervention. J. Soc. Occup. Med. 42, 129–136.

Eklund, J., 1997. Ergonomics, quality and continuous improvement—conceptual and empirical relationships in an industrial context. Ergonomics 40, 982–1001.

Evans, S.M., Kilduff, H.R., Joseph, B.S., Turner, E.H., 2000. Ergonomics@ford.com: using the intranet to enhance program effectiveness. In: IEA-2000, Vol. 1, HFES, San Diego, pp. 465–468.

Fredriksson, K., Bildt Thorbjörnsson, C., Hägg, G.M., Kilbom, Å., 2001. The impact on musculoskeletal disorders of changing physical and psychosocial work environment conditions in the automobile industry. Int. J. Ind. Ergon. 28, 31–45.

Gjessing, C., Schoenborn, T., Cohen, A. (Eds.), 1994. Participatory Ergonomic Interventions in Meatpacking Plants. NIOSH, Cincinnati.

Gleaves, S.M., Mercurio, J.J., 1991. Ergonomic circles in assembly line manufacturing. In: Pulat, B.M., Alexander, D.C. (Eds.), Industrial ergonomics, case studies. Industrial Engineering & Management Press, Norcross, GA, pp. 287–293.

GM, 2000. Manufacturing ergonomics. Recommendations ERG 1.2, General Motors Technical Center, Warren, MI.

Hagberg, M., Silverstein, B., Wells, R., Smith, M.J., Hendrick, H., Carayon, P., Pérusse, M., 1995. Work Related Musculoskeletal Disorders (WMSDs): A Reference Book for Prevention. Taylor & Francis, London.

Hagberg, M., Buckle, P., Fine, L., Franzblau, A., Kilbom, Å., Menckel, E., Punnett, L., Riihimäki, H., Silverstein, B., Viikari-Juntura, E., 1997. Health surveillance of work-related musculoskeletal disorders as a tool in ergonomics. In: Seppälä, P., Luopajärvi, T., Nygård, H., Mattila, M. (Eds.), IEA'97. Finnish Institute of Occupational Health, Tampere, pp. 274–276.

Hägg, G., 1998. Biofeedback, In: Mital, A., Kumar, S. (Eds.), Industrial and Occupational Ergonomics. Users' Encyclopedia CD-ROM, Cincinnati. Int. J. Ind. Eng.

Halpern, C., Dawson, K., 1997. Design and implementation of a participatory ergonomics program for machine sewing tasks. Int. J. Ind. Ergon. 20, 429–440.

Helander, M., Burri, G., 1995. Cost effectiveness of ergonomics and quality improvements in electronics manufacturing. Int. J. Ind. Ergon. 15, 137–151.

Helander, M., Nagamichi, M. (Eds.), 1992. Design for Manufacturability: a Systems Approach to Concurrent Engineering and Ergonomics. Taylor & Francis, London.

Herring, C., Wick, J., 1998. Reducing the probability of ergonomics related injuries in manufacturing. In: Kumar, S. (Ed.), Advances in Occupational Ergonomics and Safety, Vol. 2. IOS Press, Amsterdam, pp. 69–72.

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

Jimmerson, D.G., 1998. Ergonomics analysis software in vehicle manufacturing/assembly—a comprehensive approach. In: Kumar, S. (Ed.), Advances in Occupational Ergonomics and Safety, Vol. 2, IOS Press, Amsterdam, pp. 661–664.

Johansson Hanse, J., Forsman, M., 2001. Identification and analysis of unsatisfactory psychosocial work situations: a participatory approach employing video-computer interaction. Appl. Ergon. 32, 23–29.

Joseph, B., 2003. Corporate ergonomics programme at The Ford Motor Company. Appl. Ergon. 34 (1), 23–28.

Joseph, B., Long, M. (Eds.), 1991. Fitting Jobs to People—an Ergonomics Process. The UAW-Ford National Joint Committee on Health and Safety, Dearborn.

Kadefors, R., Forsman, M., 2000. Ergonomic evaluation of complex work: a participative approach employing video-computer interaction, exemplified in a study of order picking. Int. J. Ind. Ergon. 25, 435–445.

Kilbom, Å., 1995. Questionnaire—experience with the Nordic Questionnaires. In: Hagberg, M., Viikari-Juntura, E., Grieco, A. (Eds.), Active Health Surveillance of Work-related Musculoskeletal Disorders: an International course and workshop, Vol. 36, Undersökningsrapport, NIWL, pp. 9–10.

Klatte, T., Daetz, W., Laurig, W., 1997. Quality improvement through capable processes and ergonomic design. Int. J. Ind. Ergon. 20, 399–411.

Laitinen, H., Saari, J., Kivistö, M., Rasa, P., 1998. Improving physical and psychosocial working conditions through a participatory ergonomic process. A before-after study at an engineering workshop. Int. J. Ind. Ergon. 21, 35–45.

Lillrank, P., Kano, N., 1989. Continuous improvements—quality control circles in Japanese industry. University of Michigan, Ann Arbor.

McAtamney, L., Corlett, E.N., 1993. RULA: a survey method for the investigation of work-related upper limb disorders. Appl. Ergon. 24, 91–99.

McKenzie, F., Storment, J., Van Hook, P., Armstrong, T., 1985. A program for control of repetitive trauma disorders associated with hand tool operations in a telecommunications manufacturing facility. Am. Ind. Hyg. Assoc. J. 46, 674–678.

Moore, J., Garg, A., 1998. The effectiveness of participatory ergonomics in the red meat packing industry. Evaluation of a corporation. Int. J. Ind. Ergon. 21, 47–58.

Moreau, M., 2003. Corporate ergonomics programme at automobiles Peugeot-Sochaux. Appl. Ergon. 34 (1), 29–34.

Munck-Ulfsfält, U., Falck, A., Forsberg, A., Dahlin, C., Eriksson, A., 2003. Corporate ergonomics programme at Volvo Car Corporation. Appl. Ergon. 34 (1), 17–22.

NBOSH, 1998. Ergonomics for the prevention of musculoskeletal disorders. AFS 1998:1E, Swedish National Board of Occ Safety & Health, Solna.

NBOSH, 1999. Occupational diseases and occupational accidents 1997. Official statistics, National Board of Occupational Safety and Health, Stockholm.

Niggebrugge, D., Schelle, D., 1999. Common sense at GTI. In: Wikström, B., Hägg, G. (Eds.), Corporate Initiatives in Ergonomics, Arbete & Hälsa 1999:10, NIWL, Stockholm, pp. 100–103.

Noro, K., Imada, A. (Eds.), 1991. Participatory Ergonomics. Taylor & Francis, London.

Odenrick, P., Arvidsson, I., 2000. Ergonomic change processes in the production of an industrial company. In: IEA-2000, Vol. 5. San Diego, HFES, pp. 136–137.

Oriet, L., Ewasyshyn, F., 1998. Ergonomic implications for new technology guidelines for automotive manufacturers. In: Kumar, S. (Ed.), Advances in Occupational Ergonomics and Safety, Vol. 2. IOS Press, Amsterdam, pp. 657–660.

Oxenburgh, M., 1991. Increasing productivity and profit through health and safety—case studies in successful occupational health and safety practice. CCH International, North Ryde, NSW, Australia.

Oxenburgh, M.S., 1997. Cost-benefit analysis of ergonomics programs. Am. Ind. Hyg. Assoc. J. 58, 150–156.

Parenmark, G., Engvall, B., Malmkvist, A.-K., 1988. Ergonomic on-the-job training of assembly workers. Appl. Ergon. 19, 143–146.

Piotrowski, R., 2000. Ergonomic self reliance. A structured approach. In: IEA-2000, Vol. 2. HFES, San Diego, pp. 450–453.

Porter, M., 1998. Justifying the incorporation of ergonomics into organisational strategy—beyond single issue solving. In: Kumar, S. (Ed.), Advances in Occupational Ergonomics and Safety, Vol. 2. IOS Press, Amsterdam, pp. 119–122.

Punnett, L., Bergqvist, U., 1997. Visual display unit work and upper extremity musculoskeletal disorders—a review of epidemiological findings. Vol. 16. Arbete & Hälsa 1997:16, Arbetslivsinstitutet.

Robertson, M.M., Robinson, M., Chen, P., 2000. Office ergonomic interventions: strategies and practices. In: IEA-2000, Vol. 2. HFES, San Diego, pp. 165–168.

Ros, M., 1999. Högst fem steg (In Swedish). Occupational health clinic, Karolinska hospital, Stockholm.

Schibye, B., Skov, T., Ekner, D., Christiansen, J., Sjøgaard, G., 1995. Musculoskeletal symptoms among sewing machine operators. Scand. J. Work Environ. Health 21, 427–434.

Siffer, L., Jimmerson, G., 2000. Electrical connector acceptability rating (ECAR): ergonomic guidelines for electrical connectors for vehicle component assembly. In: IEA-2000, Vol. 5. HFES, San Diego, pp. 344–346.

Smith, M., 1994. A case study of a participatory ergonomics and safety program in a meat processing plant. In: McFadden, S., Innes, L., Hill, M. (Eds.), IEA-94, Vol. 6. HFAC, Toronto, pp. 114–116.

Smyth, J., 2003. Corporate ergonomics programme at BCM Airdrie. Appl. Ergon. 34 (1), 39–43.

Stephens, A., Vitek, M., 1998. Dynamic impact forces for vehicle assembly measurement guidelines. In: Kumas, S. (Ed.), Advances in Occupational Ergonomics and Safety, Vol. 2. IOS Press, Amsterdam, pp. 678–681.

Stroud, S., 1999. Ergonomics at SAAB, from design to the shop floor and back again. In: Wikström B.O., Hägg G.M. (Eds.) Corporate initiatives in Ergonomics, Arbete & Hälsa 1999:10, NIWL, Stockholm, pp. 59–61.

Sugimoto, Y., Iritani, T., Koide, I., 1998. Strategy for health and safety management at an automobile company. In: Kumar, S.

(Ed.), Advances in Occupational Ergonomics and Safety, Vol. 2. IOS Press, Amsterdam, pp. 669–672.

Svensson, I., Sandström, R., 1995. Ergonomic strain assessment guidelines, SAAB production. SAAB Automobile AB, Trollhättan.

Svensson, I., Sandström, R., 1997. Ergonomic strain assessment guidelines, SAAB design, SAAB Automobile AB, Trollhättan.

SWEA, 2001. Systematic Work Environment Management, AFS 2001:1, Swedish Work Environment Agency, Solna.

Westgaard, R., Winkel, J., 1997. Ergonomic intervention research for improved musculoskeletal health: a critical review. Int. J. Ind. Ergon. 20, 463–500.

Wilson, J., 1999. Interactions as the focus for human centered systems. In: Axelsson, J., Bergman, B., Eklund, J. (Eds.), TQM and Human Factors, Vol. 1. Centre for studies of humans, technology and organization, Linköping, pp. 35–43.

Winkel, J., Mathiassen, S.E., 1994. Assessment of physical work load in epidemiologic studies: concepts, issues and operational considerations. Ergonomics 37, 979–988.

Womack, J., Jones, D., Roos, D., 1990. The Machine that Changed the World. Rawson Associates, New York.

11

Biomechanical Basis for Ergonomics

William S. Marras
The Ohio State University

11.1 Biomechanic Analyses and Ergonomics

In 1978, E.R. Tichauer published a book entitled *The Biomechanical Basis of Ergonomics* (Tichauer, 1978). This book introduced much of the world to the concept of applying engineering techniques to the human body so that the limits of exposure could be identified. Since this time much has changed in the fields of ergonomics and biomechanics. However, his approaches to addressing occupationally related musculoskeletal problems remain the same to this day. Dr. Tichauer's book serves as the motivation for this chapter.

11.1.1 Definitions

Biomechanics can be defined as an interdisciplinary field in which information from both the biological sciences and engineering mechanics is used to assess the function of the body. A major assumption of occupational biomechanics is that the body behaves according to the laws of Newtonian mechanics. By definition, "mechanics is the study of forces and their effects on masses" (Kroemer, 1987). The object of interest in an occupational ergonomics context is most often a quantitative assessment of mechanical loading that occurs within the musculoskeletal system. The goal of an occupational biomechanics assessment is to quantitatively describe the musculoskeletal loading that occurs during work so that one can derive an appreciation for the degree of risk associated with an occupationally related task. The characteristic that distinguishes occupational biomechanics analyses from other types of ergonomic analyses is that the comparison is quantitative in nature. The quantitative nature of occupational biomechanics permits ergonomists to address the question of "how much exposure to the occupational risk factors is too much exposure?"

The portion of biomechanics dealing with ergonomics issues is often labeled industrial or occupational biomechanics. Chaffin et al. (1999) have defined occupational biomechanics as "the study of the physical interaction of workers with their tools, machines, and materials so as to enhance the worker's performance while minimizing the risk of musculoskeletal disorders." This chapter will address occupational biomechanical issues exclusively in this ergonomics framework.

11.1.2 Occupational Biomechanics Approach

The approach to biomechanical assessment is to characterize the human-work system situation through a mathematical representation or model. The idea behind such models is to represent the various underlying biomechanical concepts through a series of rules or equations in a "system" or model that helps us understand how the human would be affected by exposure to work. One can think of a biomechanical model as the "glue" that holds our logic together when considering the various factors that would affect risk in a specific work situation.

An advantage of representing the worker in a biomechanical model is that the model permits one to quantitatively consider the *trade-offs* associated with risk to various parts of the body in the design of a workplace. When one considers biomechanical rationale, one finds that it is difficult to accommodate all parts of the body in an ideal biomechanical environment. It is often the case that in attempting to accommodate one part of the body, the biomechanical situation at another body site is compromised. Therefore, the key to the proper application of biomechanical principles is to consider the appropriate biomechanical trade-offs associated with various parts of the body as a function of the work requirements and the various workplace design options. For this reason, this chapter will focus upon the information required to develop proper biomechanical reasoning when considering a workplace. The chapter will first present and explain a series of key concepts that constitute the underpinning of biomechanical reasoning. Next, these concepts will be applied to different parts of the body. Once this reasoning is developed an attempt will be made to examine how the various biomechanical concepts must be considered collectively in terms of trade-off, when designing a workplace from an ergonomic perspective under realistic conditions. This chapter will demonstrate that one *cannot* successfully practice ergonomics by simply memorizing a set of "ergonomic rules" (e.g., keep the wrist straight or don't bend from the waist when lifting). These types of rule-based design strategies ultimately result in sub-optimizing the workplace ergonomic conditions.

11.2 Biomechanical Concepts

11.2.1 The Load — Tolerance Construct

The fundamental concept in the application of occupational biomechanics to ergonomics is that one should design workplaces so that the load imposed upon a structure does not exceed the tolerance of the structure. This basic concept is illustrated in Figure 11.1. The figure illustrates the traditional concept of biomechanical risk in occupational biomechanics (McGill, 1997). A loading pattern is developed on a body structure that is repeated as the work cycles recur during a job. The structure tolerance is also shown in this figure. If the magnitude of the load imposed on a structure is far less than tissue tolerance, then the task is considered safe and the magnitude of the difference between the load and the tolerance is considered the safety margin. Also implicit in this figure, is the idea that risk occurs when the imposed load exceeds the tissue tolerance. While tissue tolerance is defined as the force that

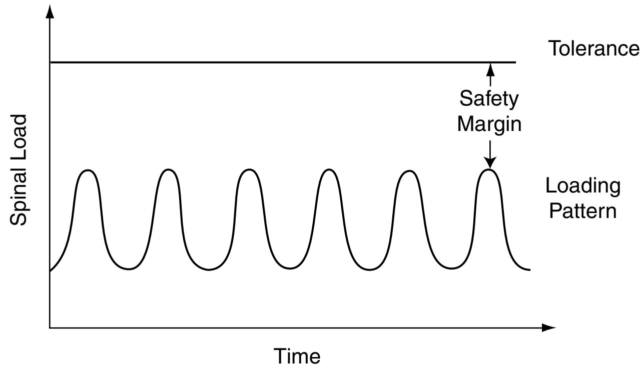

FIGURE 11.1 Traditional concept of biomechanical risk.

results in tissue damage, some ergonomists are beginning to expand the concept of tolerance to include not only mechanical tolerance of the tissue, but also the point at which the tissue exhibits an inflammatory reaction.

Industrial tasks are becoming more repetitive involving lighter loads. The conceptual load tolerance model can also be adjusted to also account for this type of risk exposure. As shown in Figure 11.2, occupational biomechanics logic can account for the fact that with repetitive loading the tolerance of the structure tissue may decrease over time to the point where it is more likely that the structure loading will exceed the structure tolerance and result in injury or illness. Thus, occupational biomechanical models and logic are moving towards systems that consider manufacturing and work trends in the workplace and attempt to represent these observations (such as cumulative trauma disorders) in the model logic.

11.2.2 Acute vs. Cumulative Trauma

It is well recognized that in occupational settings two types of trauma can affect the human body and lead to musculoskeletal disorders. First, *acute* trauma can occur, which refers to an application of force that is so large that it exceeds the tolerance of the body structure during an occupational task. Thus, acute trauma is typically associated with large exertions of force that would occur infrequently. For example, an acute trauma can occur when a worker is asked to lift an extremely heavy object as when moving a heavy part. This situation would relate to a peak load pattern that exceeded the load tolerance

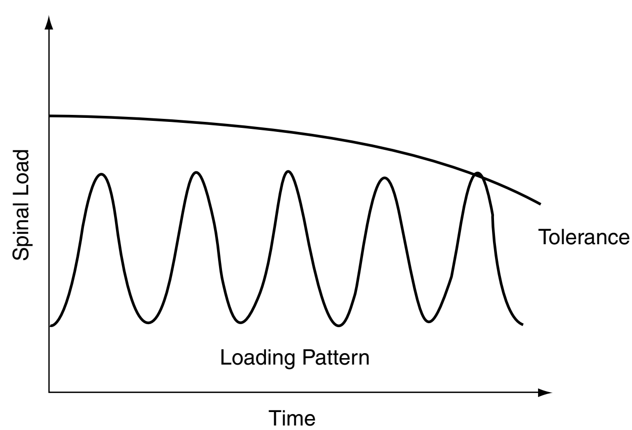

FIGURE 11.2 Realistic scenario of biomechanical risk.

in Figure 11.1. *Cumulative* trauma, on the other hand, refers to the repeated application of force to a structure that tends to wear down a structure, thus, lowering the structure tolerance to the point where the tolerance is exceeded through a reduction of the tolerance limit. This situation was illustrated in Figure 11.2. Cumulative trauma represents more of a "wear and tear" on the structure. This type of trauma is becoming far more common in the workplace since more repetitive jobs are becoming common in industry and is the mechanism of concern for many ergonomics evaluations.

Cumulative trauma can initiate a process that can result in a tissue reactive cycle that is extremely difficult to break. This process is illustrated in Figure 11.3. The cumulative trauma process begins by exposing the worker to manual exertions that are either frequent (repetitive) or prolonged. This repetitive application of force can affect either the tendons or the muscles of the body. If the tendons are affected, the following sequence occurs. The tendons are subject to mechanical irritation when they are repeatedly exposed to high levels of tension and groups of tendons may rub against each other. The physiologic reaction to this mechanical irritation can result in inflammation and swelling of the tendon. This swelling will stimulate the nociceptors surrounding the structure and signal the central control mechanism (brain) via pain perception that a problem exists. In response to this pain, the body will attempt to control the problem via two mechanisms. First, the muscles surrounding the irritated area will coactivate in an attempt to stabilize the motion of the tendons or stiffen the structure. Since motion will further stimulate the nociceptors and result in further pain, motion avoidance is often indicative of the start of a cumulative trauma disorder. Second, in an attempt to reduce the friction occurring within the tendon, the body will increase its production of synovial fluid within the tendon sheath. However, given the limited space available between the tendon and the tendon sheath the increased production of synovial fluid often exacerbates the problem by further expanding the tendon sheath and, in thus, further stimulating the surrounding nociceptors. As indicated in the figure, this initiates a viscous cycle where the response of the tendon to the increased friction results in a reaction (inflammation and the increased production of synovial fluid) that exacerbates the problem. Once this cycle is initiated it is very difficult to stop and often anti-inflammatory agents are required. This process results in chronic joint pain and a series of musculoskeletal reactions such as reduced strength, reduced tendon motion, and reduced mobility. Collectively, these reactions result in a functional disability.

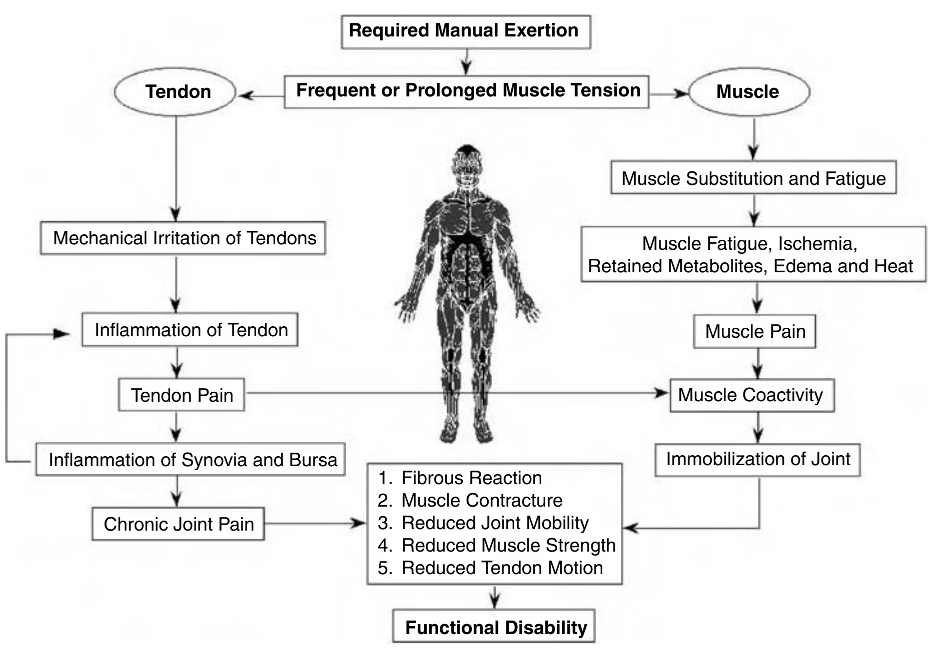

FIGURE 11.3 Sequence of events in CTDs.

A similar process occurs if the muscles are affected by cumulative trauma as opposed to the tendons. Muscles can be easily overloaded when they become fatigued. Fatigue can lower the tolerance to stress and can result in microtrauma to the muscle fibers. This microtrauma typically means that the muscle is partially torn and the tear will cause capillaries to rupture and result in swelling, edema, or inflammation near the site of the tear. This process can stimulate nociceptors and result in pain. As with cumulative trauma to the tendons, the body reacts by cocontracting the surrounding musculature and thereby minimizing the motion of the joint. Since the tendons are not involved with cumulative trauma to the muscles there is no increased production of synovial fluid. However, the end result is the same series of musculoskeletal reactions resulting from tendon irritation (i.e., reduced strength, reduced tendon motion, and reduced mobility). The ultimate result of this process is once again a functional disability.

Even though the stimulus associated with the cumulative trauma process is somewhat similar between tendons and muscles there is a significant difference in the time required to heal from the damage to a tendon compared to a muscle. The mechanism of repair for both the tendons and muscles is dependent upon blood flow to the damaged structure. Blood provides nutrients for repair as well as dissipates waste materials. However, the blood supply to a tendon is just a fraction (typically about 5% in an adult) of that supplied to a muscle. Thus, given an equivalent strain to a muscle and a tendon, the muscle will heal rapidly (in about 10 days if not reinjured), whereas the tendon could take months (20 times longer) to accomplish the same level of repair. For this reason, ergonomists must be particularly vigilant in the assessment of workplaces that could pose a danger to the tendons of the body. This lengthy repair process also explains why most ergonomics processes place a high value on identifying potentially risky jobs prior to a lost time incident through mechanisms such as discomfort surveys.

11.2.3 Moments and Levers

Biomechanical loads are *not* defined solely by the magnitude of weight supported by the body. The position of the weight relative to the axis of rotation of the joint of interest defines the imposed load on the body and is referred to as a *moment.* Thus, a moment is defined as the product of force and distance. For example, a 50 N mass held at a horizontal distance of 75 cm (0.75 meters) from the shoulder joint imposes a moment of 37.5 Nm ($50\ \mathrm{N} \times 0.75\ \mathrm{m}$) on the shoulder joint, whereas, the same weight held at a horizontal distance of 25 cm from the shoulder joint imposes a moment or load of only 12.5 Nm ($50\ \mathrm{N} \times 0.25\ \mathrm{m}$) on the shoulder. Thus, the load on a joint is a function of where the load is held relative to the joint and the mass of the weight held. Joint load is not simply a function of weight.

As implied by this example, moments are a function of the mechanical lever systems of the body. The musculoskeletal system can be represented by a system of levers and these are the lever systems that are used to describe the tissue loads with a biomechanical model. Three types of lever systems are present in the human body. First-class levers are those that have a fulcrum in the middle of the system, an imposed load on one end of the system and an opposing (*internal*) load imposed on the opposite end of the system. As will be discussed later, the trunk is an example of a first-class lever. In this example, the spine serves as the fulcrum. As the worker lifts, a moment is imposed anterior to the spine due to the object weight times the distance of the object from the spine. This moment is counterbalanced by the activity of the back musculature, however, back muscles are at a mechanical disadvantage since the distance between the back muscles and the spine is much less than the distance between the object lifted and the spine. A second-class lever system can be found in the lower extremity. In a second-class lever system the fulcrum is on one end of the lever, the opposing force is on the other end of the system and the applied load is in between these two. In the body, the foot is a good example of this lever system. In this example, the ball of the foot acts as the fulcrum, the load is applied through the tibia or bone of the lower leg. The restorative force is applied through the gastrocnemius or calf muscle. In this manner the muscle activates and causes the body to move about the fulcrum or ball of the foot and move the body forward. Finally, a third-class lever system is one where the fulcrum is located at one end of the system, the applied load acts at the other end of the system and the opposing

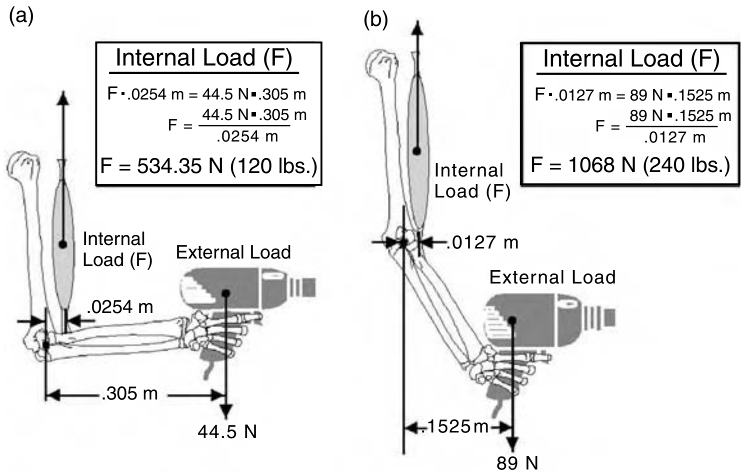

FIGURE 11.4 An example of an anatomical third-class lever (a) demonstrating how the mechanical advantage changes as the elbow position changes (b).

force acts in between the two. An example of this system in the human body is the elbow joint and is shown in Figure 11.4.

11.2.4 External and Internal Loading

Two types of forces can impose loads on a tissue during work. *External* loads refer to those forces that are imposed on the body as a direct result of gravity acting upon an external object being manipulated by the worker. For example, in Figure 11.4a, the tool held in the worker's hand is subject to the forces of gravity, which impose a 44.5 N (10 lb) external load at a distance from the elbow joint of 30.5 cm (12 inches). However, in order to maintain equilibrium, this external load must be counteracted by an *internal* load that is supplied by the muscles of the body. Figure 11.4a also shows that the internal load (muscle) acts at a distance relative to the elbow joint that is much closer to the fulcrum than the external load (tool). Thus, the internal load or force is at a biomechanical disadvantage and must be much larger (534 N or 120 lb) than the external load (44.5 N or 10 lb) in order to keep the musculoskeletal system in equilibrium. As shown in this example it is not unusual for the magnitude of the internal load to be much greater (typically 10 times greater) than the external load. Thus, it is typically the internal loading that contributes mostly to the cumulative trauma of the musculoskeletal system during work. The sum of the external load and the internal load define the total loading experienced at the joint. When evaluating a workstation the ergonomist must not only consider the externally applied load but must be particularly sensitive to the magnitude of the internal forces that can load the musculoskeletal system.

11.2.5 Factors Affecting Internal Loading

The previous discussion has discussed the importance of understanding the relationship between the external loads imposed upon the body and the internal loads generated by the force generating mechanisms within the body. The key to proper ergonomic design involves designing workplaces so that the internal loads are minimized. One can consider the internal forces as both the component that loads the tissue as well as a structure that can be subject to over-exertion. Muscle strength or capacity can be considered as a tolerance measure. If the forces imposed on the muscles and tendons as a result of the task exceed the strength of the muscle or tendon an injury is possible. In general, three components of the physical work environment (biomechanical arrangement of the musculoskeletal lever system, length–strength relationships, and temporal relationships) can be manipulated in order to facilitate this goal and serve as the basis for many ergonomic recommendations.

11.2.5.1 Biomechanical Arrangement of the Musculoskeletal Lever System

The posture required by the design of the workplace can affect the arrangement of the body's lever system, and thus, can greatly affect the magnitude of the internal load required to support the external load. The arrangement of the lever system can influence the magnitude of the external moment imposed upon the body as well as dictate the magnitude of the internal forces and the subsequent risk of cumulative trauma. Consider the biomechanical arrangement of the elbow joint that is shown in Figure 11.4. In Figure 11.4a, the mechanical advantage of the internal force generated by the biceps muscle and tendon is defined by a posture that keeps one's arm bent at a 90° angle. If one palpates the tendon and inserts the index finger between the joint center and the tendon, one can gain an appreciation for the internal moment arm distance. One can also appreciate how this internal mechanical advantage can change with posture. With the index finger still inserted between the elbow joint and the tendon and if the arm is slowly straightened one can appreciate how the distance between the tendon and the joint center of rotation is significantly reduced. If the imposed moment about the elbow joint is held constant (as shown in Figure 11.4b by a heavier tool) under these conditions, the mechanical advantage of the internal force generator is significantly reduced. Thus, the internal moment must generate greater force in order to support the external load. This greater force is transmitted through the tendon and can increase the risk of cumulative trauma. Therefore, the positioning of the mechanical lever system (which can be accomplished though work design) can greatly affect the internal load transmission within the body. The same task can be performed in a variety of ways but some of these positions are much more costly in terms of loading of the musculoskeletal system than others.

11.2.5.2 Length–Strength Relationship

Another important relationship in defining the load on the musculoskeletal system is the length–strength relationship of the muscles. Figure 11.5 shows this relationship. The active portion of this figure refers to structures that actively generate force such as muscles. The figure indicates that when muscles are close to their resting length (generally seen in the fetal position), they have the greatest capacity to generate force. However, when the muscle length deviates from this resting position the capacity to generate force is greatly reduced because the cross-bridges between the components of the muscle proteins become inefficient. Hence, when a muscle stretches or when a muscle attempts to generate force while at a short length the ability to generate force is greatly diminished. Note also, as indicated in Figure 11.5 that passive tissues in the

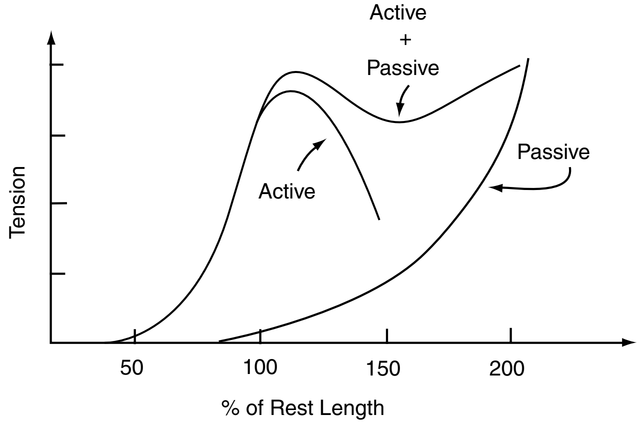

FIGURE 11.5 Length–tension relationship for a human muscle. (Adapted from Basmajian, J.V. and De Luca, C.J., *Muscles Alive: Their Functions Revealed by Electromyography*, 5th ed., Williams and Wilkins, Baltimore, MD, 1985. With permission.)

FIGURE 11.6 Position-force diagram produced by flexion of the forearm in pronation. "Angle" refers to included angle between the longitudinal axes of the forearm and upper arm. The highest parts of the curve indicate the configurations where the biomechanical lever system is most effective. (Adapted from Chaffin, D.B. and Andersson, G.B., *Occupational Biomechanics*, John Wiley & Sons, Inc. New York, 1991. With permission.)

muscle (and ligaments) can generate tension when muscles are stretched. Thus, the orientation of the muscle fibers during a task can greatly influence the force available to perform work and can, therefore, influence risk by altering the available internal force within the system. A given tension on a muscle can either tax the muscle greatly or be a minimum burden on the muscle. What might be considered a moderate force for a muscle at the resting length can become the maximum force a muscle can produce when it is in a stretched or contracted position, thus, increasing the risk of muscle strain. When this relationship is considered in conjunction with the mechanical load placed on the muscle and tendon via the arrangement of the lever system, the position of the joint arrangement becomes a major factor in the design of the work environment. It is typically the case that the length–strength relationship interacts synergistically with the lever system. Figure 11.6 shows the effect of elbow position on the force generation capability of the elbow. This figure indicates that position can have a dramatic effect on force generation. As already discussed this position can also have a great effect on internal loading of the joint and the subsequent risk of cumulative trauma.

11.2.5.3 Force–Velocity Relationship

Motion can profoundly influence the ability of a muscle to generate force and, therefore, load the biomechanical system. Motion can be a benefit to the biomechanical system if momentum is properly used or it can increase the load on the system if the worker is not taking advantage of momentum. The relationship between muscle velocity and force generation is shown in Figure 11.7. This figure indicates that, in general, the faster the muscle is moving the greater the reduction in force capability of the muscle. As with most of the biomechanical principles discussed in this chapter, this reduction in muscle capacity can result in the muscle strain that can occur at a lower level of external loading and a subsequent increase in the risk of cumulative trauma. In addition, this effect is considered in many dynamic ergonomic biomechanical models.

11.2.5.4 Temporal Relationships

11.2.5.4.1 Strength Endurance

Strength can be considered both an internal force as well as a tolerance limiter, but it is important to realize that strength is transient. A worker may generate a great amount of strength during a one-time exertion. However, if the worker is required to exert his strength either repeatedly or for a prolonged period of time, the amount of force that the worker can generate is reduced dramatically. Figure 11.8 demonstrates this relationship during an isometric exertion. The dotted line in this figure indicates the maximum force generation capacity of a static exertion of force over time. Maximum force output is only generated for a very brief period of time. As time increases, strength output decreases exponentially and levels off at about 20% of maximum after about 7 min. Similar trends occur under

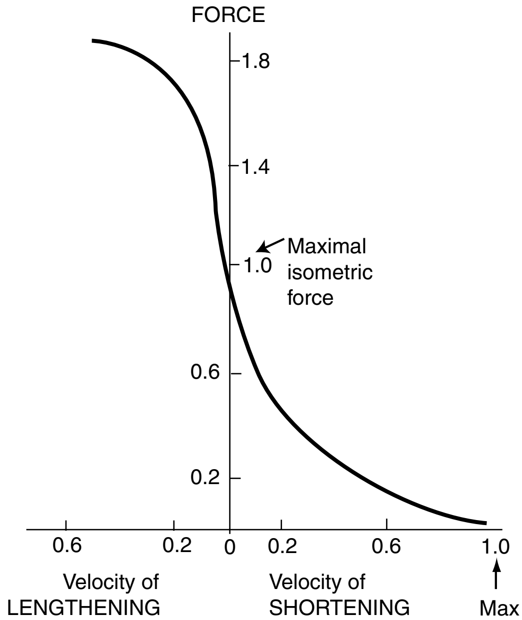

FIGURE 11.7 Influence of velocity upon muscle force (Adapted from *The Textbook of Work Physiology*, McGraw-Hill, 1977. With permission.)

repeated dynamic conditions. This indicates that if it is determined that a task requires a large portion of a workers' strength, one must consider how long that portion of the strength is required in order to ensure that the work does not strain the musculoskeletal system.

11.2.5.4.2 Rest Time

As mentioned previously, the risk of cumulative trauma increases when the capacity to exert force is exceeded by the force requirements of the job. Another factor that can affect this strength capacity (and tolerance to muscle strain) is rest time. Rest time has a profound effect on the ability to exert force. Figure 11.9

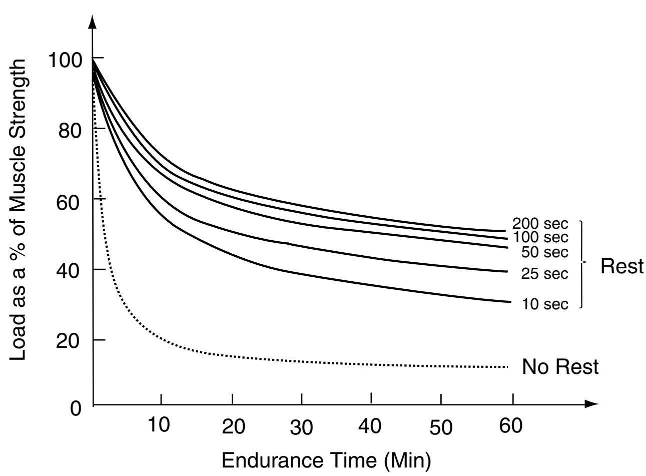

FIGURE 11.8 Forearm flexor muscle endurance times in consecutive static contractions of 2.5 sec duration with varied rest periods. (Adapted from Chaffin, D.B. and Andersson, G.B., *Occupational Biomechanics*, John Wiley & Sons, Inc. New York, 1991. With permission.)

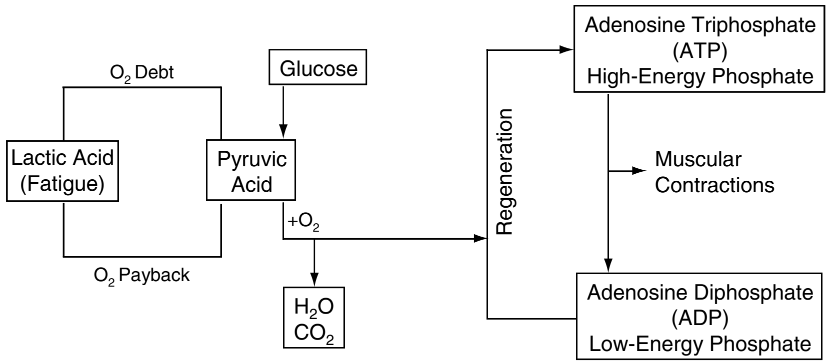

FIGURE 11.9 The body's energy system during work. (Adapted from Grandjean, E., *Fitting the Task to the Man: An Ergonomic Approach*, Taylor & Francis, Ltd., London, 1982. With permission.)

shows how energy for a muscular contraction is regenerated during work. Adenosine triphosphate (ATP) is required to produce a significant muscular contraction. ATP changes to adenosine diphosphate (ADP) once a muscular contraction has occurred. This ADP must be converted to ATP in order to enable another muscular contraction. This conversion can occur with the addition of oxygen to the system. If oxygen is not present, then the system goes into oxygen debt and there is insufficient ATP for a muscular contraction. Thus, this flow chart indicates that oxygen is a key ingredient to maintain a high level of muscular exertion. Oxygen is delivered to the target muscles via the blood flow. However, under static exertions the blood flow is reduced and there is a subsequent reduction in the blood flow to the muscle. This restriction of blood flow and subsequent oxygen deficit are responsible for the rapid decrease in force generation over time as shown in Figure 11.8. The solid lines shown in Figure 11.8 indicate how the force generation capacity of the muscles increase when different amounts of rest are permitted in a fatiguing exertion. As more and more rest time is permitted, increases in force generation are achieved when more oxygen is delivered to the muscle and more ADP can be converted to ATP. This relationship also shows that any more than about 50 sec of rest, under these conditions, does not result in a significant increase in force generation capacity of the muscle. Practically, this indicates that in order to optimize the strength capacity of the worker and minimize the risk of muscle strain, a schedule of frequent and brief rest periods would be more beneficial than lengthy infrequent rest periods.

11.2.6 Load Tolerance

As mentioned previously, occupational biomechanical analyses must consider not only the loads imposed upon a structure but also the ability of the structure to withstand or tolerate a load during work. This section will briefly review the knowledge base associated with body structure tolerances.

11.2.6.1 Muscle, Ligament, Tendon, and Bone Capacity

The exact tolerance characteristics of human tissues such as muscles, ligaments, tendons, and bones loaded under various working conditions are difficult to estimate. Tolerances of the structures in the body vary greatly under similar loading conditions. In addition, tolerance depends upon many other factors such as strain rate, age of the structure, frequency of loading, physiologic influences, heredity, conditioning, and many unknown factors. Furthermore, it is not possible to measure these tolerances under human *in vivo* conditions. Therefore, most of the published estimates of tissue tolerance have been derived from various animal and/or theoretical sources.

11.2.6.2 Muscle and Tendon Strain

Muscle appears to be the structure that has the lowest tolerance in the musculoskeletal system. The ultimate strength of a muscle has been estimated at 32 MPa (Hoy et al., 1990). In general, it is believed that the muscle will rupture prior to the tendon in a healthy tendon (Nordin and Frankel, 1989), since tendon stress has been estimated at between 60 and 100 MPa (Nordin and Frankel, 1989; Hoy et al., 1990). Hence, as indicated in Table 11.1, there is a safety margin between the muscle failure point and the failure point of the tendon of about twofold (Nordin and Frankel, 1989) to threefold (Hoy et al., 1990).

11.2.6.3 Ligament and Bone Tolerance

Ligaments and bone tolerances within the musculoskeletal system have also been estimated. Ultimate ligament stress has been estimated at approximately 20 MPa. The ultimate stress of bone varies depending upon the direction of loading. Bone tolerance can range from as low as 51 MPa in transverse tension to over 190 MPa in longitudinal compression. Table 11.1 also indicates the ultimate stress of bone loaded in different loading conditions.

A strong temporal component to ligament recovery appears to exist. Solomonow has found that ligaments require long periods of time to regain structural integrity and compensatory muscle activities are recruited (Solomonow et al., 1998, 1999, 2000, 2002; Stubbs et al., 1998; Gedalia et al., 1999; Wang et al., 2000; Solomonow, 2004). Recovery time has been found to be several fold the loading duration and can easily exceed the typical work-rest cycles observed in industry.

11.2.6.4 Disc/Endplate and Vertebrae Tolerance

The mechanism of cumulative trauma in the disc is thought to be related to repeated trauma to the vertebral endplate. The endplate is a very thin (about 1 mm thick) structure that facilitates nutrient flow to the disc fibers (anulus fibrosis). Repeated microfracture of this vertebral endplate is thought to impair the nutrient flow to the disc fibers and thereby lead to atrophy and degeneration of the fiber. It is believed that if one can determine the level at which the endplate experiences a microfracture, one can then minimize the effects of cumulative trauma and disc degeneration within the spine. Several studies of disc endplate tolerance have been performed. Figure 11.10 shows the levels of endplate compressive loading tolerance that have been used to establish safe lifting situations at the worksite (NIOSH, 1981). This figure shows the compressive force mean (column value) as well as the compression force distribution (thin line and normal distribution curve) that would result in vertebral endplate failure (microfracture). This figure indicates that for those under 40 years of age endplate microfracture damage begins to occur at about 3432 N, of compressive load on the spine. If the compressive load is increased to 6375 N, approximately 50% of those exposed to the load will experience vertebral endplate microfracture. When

TABLE 11.1 Tissue Tolerance of the Musculoskeletal System

Structure	Estimated Ultimate Stress (σ_u) (MPa)
Muscle	32–60
Ligament	20
Tendon	60–100
Bone longitudinal loading	
Tension	133
Compression	193
Shear	68
Bone transverse loading	
Tension	51
Compression	133

Source: Adapted from Ozkaya and Nordin, *Fundamentals of Biomechanics, Equilibrium, Motion and Deformation*, Van Nostrand Reinhold, New York, 1991. With permission.

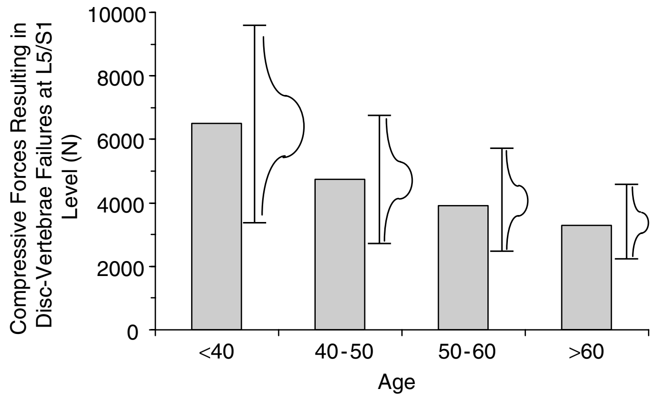

FIGURE 11.10 Mean and range of disc compression failures by age. (Adapted from National Institute for Occupational Safety and Health (NIOSH) Work practices guide for manual lifting, Department of Health and Human Services (DHHS), NIOSH, Cincinnati, OH, 81–122, 1981. With permission.)

the compressive load on the spine reaches a value of 9317 N, almost all of those exposed to the loading will experience a vertebral endplate microfracture. It should also be noted that the tolerance distribution shifts to lower levels with increasing age (Adams et al., 2000). In addition, it should be emphasized that this tolerance is based upon compression of the vertebral endplate alone. Shear and torsional forces in combination with compressive loading would be expected to further lower the tolerance of the end plate.

This distribution of risk has been widely used as the tolerance limits of the spine. However, it should be noted that others have identified different limits of vertebral endplate tolerance. Jager et al. (1991) have reviewed 13 studies of spine compressive strength and suggested different compression value limits. Their summary of these spine tolerance limits are shown in Table 11.2. These researchers have also been able to describe the vertebral compressive strength based upon an analysis of 262 values collected from 120 samples. They have related the compressive strength of the lumbar spine according to a regression equation:

$$\text{Compressive Strength (kN)} = (7.26 + 1.88\,\text{G}) - 0.494 + 0.468\,\text{G}) \cdot A \\ + (0.042 + 0.106\,\text{G}) \cdot C - 0.145 \cdot L - 0.749 \cdot \text{S},$$

TABLE 11.2 Investigations into Static Lumbar Compressive Strength

		Strength in kN	
Reference	*n*	Mean	*s.d.*
Wyss and Ulrich, 1954	8	5.89	2.24
Brown et al., 1957	5	5.20	0.54
Perey, 1957	142	5.15	2.10
Decoulx and Rienau, 1958	9	4.41	1.14
Evans and Lissner, 1959	11	3.51	1.22
Roaf, 1960	3	4.83	2.06
Eie, 1966	16	3.70	1.60
Farfan, 1973	39	3.84	1.22
Hutton et al., 1979	23	5.35	2.67
Hansson et al., 1980	109	3.85	1.71
Hutton and Adams, 1982	33	7.83	2.87
Brinckmann and Horst, 1983	22	6.42	2.00
Brinckmann et al., 1989	87	5.35	1.76
Female	132	3.97	1.50
Male	174	5.81	2.58
Total	507	4.96	2.20

Source: Adapted from Jager, Luhman, and Laurig, Int. J. Indust. Ergo., 1991. With permission.

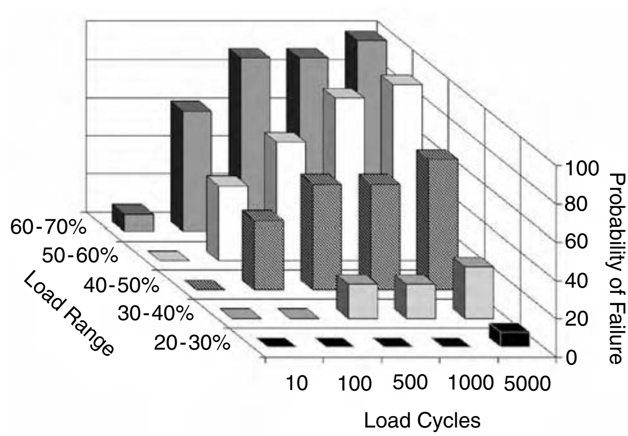

FIGURE 11.11 Probability of a motion segment to be fractured in dependence on the load range and the number of load cycles. (Adapted from Brinckmann, et al., *Clin. Biomech.*, 3(Suppl. 1), S1–S23, 1988. With permission.)

where A is the age in decade; G is the gender coded as 0 for female or 1 for male; C is the cross-sectional area of the vertebrae in cm^2; L is the the lumbar level unit where 0 is the L5/S1 disc, 1 represents the L5 vertebrae, etc. through 10, which represents the T10/L1 disc; S is the structure of interest where 0 is a disc and 1 is a vertebra.

This analysis suggests that the decrease in strength within a lumbar level is about 0.15 kN of that of the adjacent vertebrae and that the strength of the vertebrae is about 0.8 kN lower than the strength of the discs (Jager et al., 1991). Using this equation these researchers were able to account for 62% of the variability among the samples.

It has also been suggested that the tolerance limits of the spine varies as a function of frequency of loading (Brinkmann et al., 1988). Figure 11.11 indicates that spine tolerance varies as a function of spine load level and frequency of loading.

11.2.6.5 Pain Tolerance

It is believed that there are numerous pathways to pain perception associated with musculoskeletal disorders (Cavanaugh, 1995; Cavanaugh et al., 1997; Khalsa, 2004). It is important to understand these pathways since they are the basis for the structure and tissue limits employed in ergonomic logic. One can consider the quantitative limits above which a pain pathway is initiated as a tolerance limit for ergonomic purposes. While none of these pathways have been defined quantitatively, they are appealing since they represent biologically plausible mechanisms that complement the view of injury association derived from the epidemiologic literature.

In general, several broad categories of pain pathways are believed to exist that may affect the design of the workplace. These categories are associated with: (1) structural disruption, (2) tissue stimulation and pro-inflammatory response, (3) physiologic limits, and (4) psychophysical acceptance. Each of these pathways is expected to have different tolerance limits to mechanical loading of the tissue. Although many of these limits have yet to be quantitatively defined, future biomechanical assessments are expected to compare tissue loads to these limits when the dose–response relationship becomes better defined.

11.3 The Application of Biomechanics to the Workplace

11.3.1 Biomechanics of Commonly Affected Body Structures

Now that the basic concepts and principles of biomechanics relevant to ergonomics situations have been established we can apply these principles to various work situations. This section will show how one can apply these principles to various regions of the body that are typically affected by occupational tasks.

11.3.1.1 Shoulder

Shoulder pain is suspected of being one of the most under-recognized musculoskeletal disorders in the workplace. Second only to low back injury and neck pain, shoulder disorders are increasingly being recognized as a major workplace problem by those organizations that have reporting systems sensitive enough to detect such trends. The shoulder is one of the more complex structures of the body with numerous muscles and ligaments crossing the shoulder joint-girdle complex. Because of its biomechanical complexity surgical repair of the shoulder can be problematic. During many shoulder surgeries it is often necessary to damage much of the surrounding tissue in an attempt to reach the structure in need of repair. Often the target structure is small in size and difficult to reach. Thus, often at times, more damage is done to surrounding tissues than the benefits derived to the target tissue. Therefore, the best course of action is to ergonomically design work stations so that the risk of initial injury is minimized.

Since the shoulder joint is so biomechanically complex, much of our biomechanical knowledge is derived from empirical evidence. The shoulder represents a statically indeterminate system in that we can typically measure six external moments and forces acting about the point of rotation, yet, there are far more internal forces (over 30 muscles and ligaments) that must counteract the external moments. Thus, quantitative estimates of shoulder joint loading are rare.

With respect to the shoulder, optimal workplace design is typically defined in terms of preferred posture during work. Shoulder *abduction*, defined as the elevation of the shoulder in the lateral direction, is of concern when work is performed overhead. Figure 11.12 indicates shoulder performance measures in terms of both available strength and perceived fatigue while the shoulder is held in varying degrees of abduction. This figure indicates that shoulder can produce a considerable amount of strength throughout shoulder abduction angles of between 30 and 90°. However, when comparing fatigue characteristics at these same abduction angles it is apparent that fatigue increases rapidly as the shoulder is abducted above 30°. Thus, even though strength is not a problem at shoulder abduction angles upto 90°, fatigue becomes the limiting factor. Therefore, the only position of the shoulder that is acceptable from both a strength and fatigue standpoint is a shoulder abduction of at most 30°.

Shoulder *flexion* has been examined almost exclusively as a function of fatigue. Chaffin (1973) has shown that even slight shoulder flexion can influence fatigue characteristics of the shoulder musculature. Figure 11.13 and Figure 11.14 indicate the effects of vertical height of the work and horizontal distance, respectively, during shoulder flexion while seated upon fatigability of the shoulder musculature. During vertical flexion/extension (Figure 11.13), fatigue occurs more rapidly as the workers' arm becomes more elevated. This trend is most likely due to the fact that the muscles are farther from the neutral position as

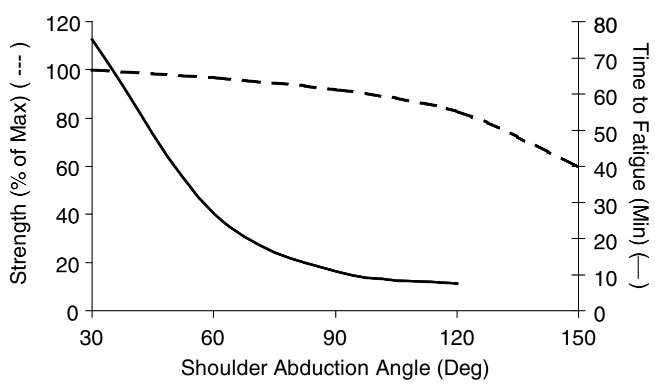

FIGURE 11.12 Shoulder abduction strength and fatigue time as a function of shoulder abducted from the torso. (Adapted from Chaffin, D.B. and Andersson, G.B., *Occupational Biomechanics*, John Wiley & Sons, Inc., New York, 1991. With permission.)

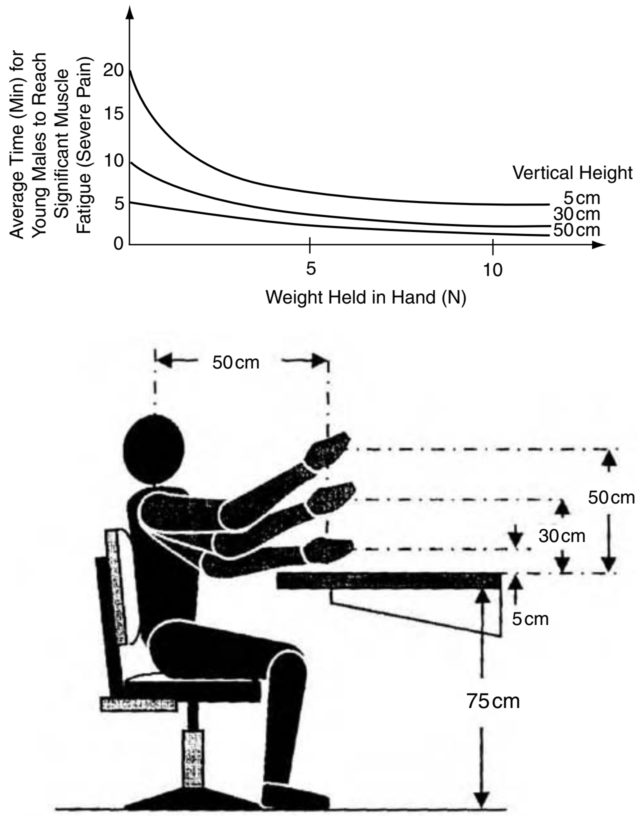

FIGURE 11.13 Expected time to reach significant shoulder muscle fatigue for varied arm flexion postures. (Adapted from Chaffin, D.B. and Andersson, G.B., *Occupational Biomechanics*, John Wiley & Sons, Inc., New York, 1991. With permission.)

the shoulder becomes more elevated thus affecting the length–strength relationship (Figure 11.5) of the shoulder muscles. Figure 11.14 shows that as the horizontal distance between the work and the body is increased, the time to reach significant fatigue is decreased. This trend is due to the fact that as a load is held further from the body, more of the external moment (force · distance) must be supported by the shoulder. Thus, the shoulder muscles must produce a greater internal force when the load is held further from the body and they fatigue quicker. Elbow supports have been shown to significantly increase the endurance time in these postures. In addition an elbow support has the effect of changing the biomechanical situation by providing a fulcrum at the elbow. Thus, the axis is rotation becomes the elbow instead of the shoulder and this makes the external moment much shorter. As shown in Figure 11.15, this not only increase the time one can maintain a posture, but also significantly increases the external load one can hold in the hand.

11.3.1.2 Neck

Neck disorders can also be associated with sustained work postures. In general, the more upright posture of the head, the less muscle activity and neck strength is required to maintain the posture. Upright neck postures also have the advantage of reducing the extent of fatigue perceived in the neck region. This relationship is shown in Figure 11.16. This trend indicates that when the head is tilted forward by 30° or more from the vertical position, the time to experience significant neck fatigue decreases rapidly. From a biomechanical standpoint, as the head is flexed forward the center of mass of the head moves forward relative to the base of support of the head (spine). Therefore, as the head is moved forward,

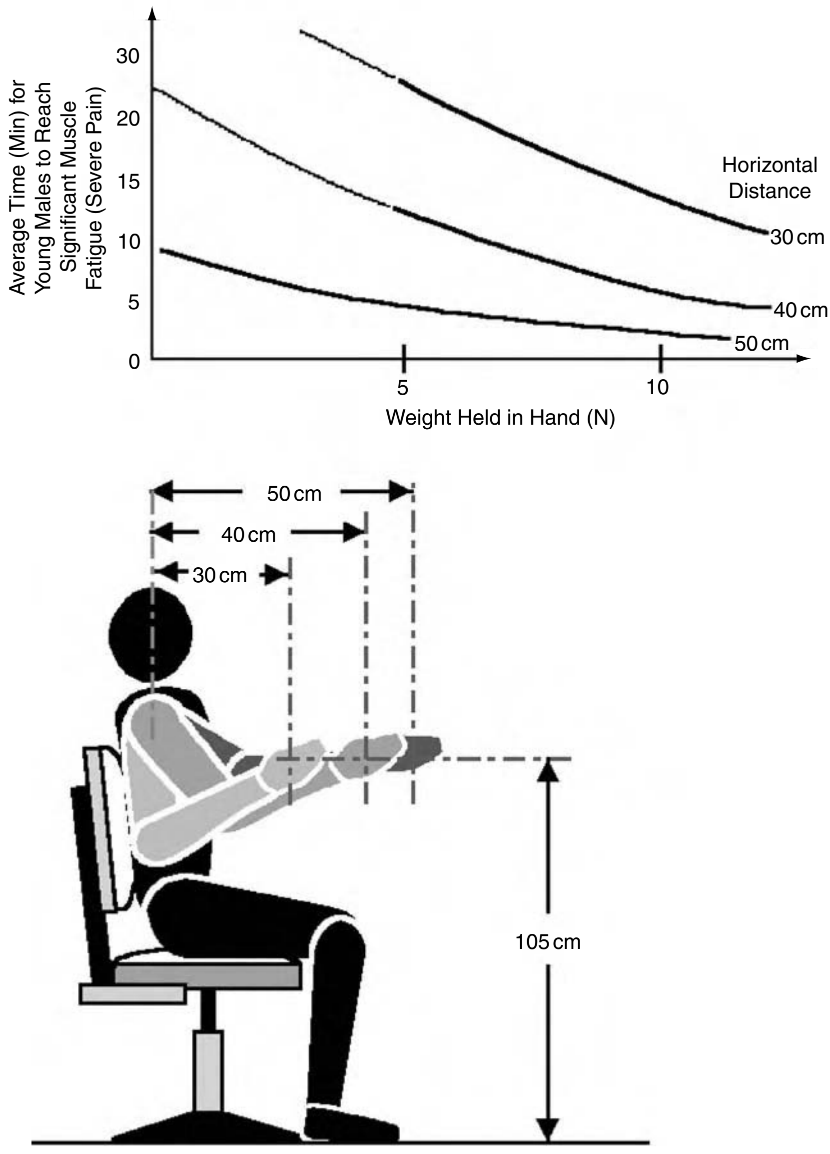

FIGURE 11.14 Expected time to reach significant shoulder muscle fatigue for different forward arm reach postures. (Adapted from Chaffin, D.B. and Andersson, G.B., *Occupational Biomechanics*, John Wiley & Sons, Inc., New York, 1991. With permission.)

more of a moment is imposed about the spine, which necessitates increased activation of the neck musculature and greater risk (probability of fatigue) since a static posture is maintained by the neck muscles. When the head is not flexed forward and is relatively upright, the neck can be positioned in such a way that minimal muscle activity is required of the neck muscles and thus fatigue is minimized.

11.3.1.3 Trade-Offs in Work Design

The key to optimal ergonomic workplace design, from a biomechanical standpoint, is to consider the biomechanical trade-offs associated with a given work situation. Trade-off considerations are necessary because it is often the case that a situation that is advantageous for one part of the body is

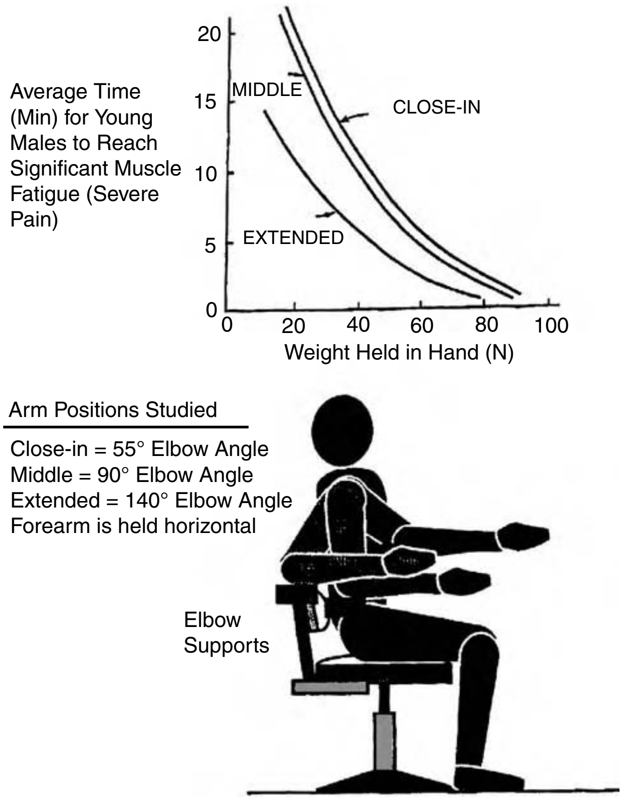

FIGURE 11.15 Expected time to reach significant shoulder and arm muscle fatigue for different arm postures and hand loads with the elbow supported. The greater the reach, the shorter the endurance time. (Adapted from Chaffin, D.B., and Andersson, G.B., *Occupational Biomechanics*, John Wiley & Sons, Inc., New York, 1991. With permission.)

disadvantageous for another part of the body. Thus, ergonomic design of the workplace requires one to consider the various trade-offs and rationales for various design options.

One common trade-off encountered in ergonomic design is the trade-off between accommodating the shoulders and accommodating the neck. This trade-off is resolved by considering the hierarchy of needs required by the task. Figure 11.17 illustrates this reasoning. The recommended height of the work is a function of the type of work that is to be performed. Precision work requires a high level of visual acuity, which becomes the greatest need in order to perform the work task. However, if the work is performed at too low of a level the head must be flexed in order to accommodate the visual requirements of the job and this becomes a problem for the neck. Therefore, in this circumstance, visual accommodation is at the top of the hierarchy of task needs, so that the work is raised to a relatively high level (95 to 110 cm above the floor) in order to accommodate vision and the neck posture. This posture accommodates the neck but creates a problem for the shoulders since they must be abducted when the work level is high. Thus, a trade-off should be considered. In this instance, ideal shoulder posture is sacrificed in order to accommodate the neck since the visual requirements of the job represent the greater priority for work performance, whereas, the minimal shoulder strength is required for precision work and, thus, represents a lower priority. Thus, visual accommodation is given a higher priority in the hierarchy of task needs and this criterion must be given priority over any other criteria. Besides, the shoulder problems can be minimized by providing wrist or elbow supports at the workplace.

The other extreme example of the working height situation involves heavy work. The greatest demand on the worker during heavy work involves a high degree of arm strength, whereas, visual requirements in

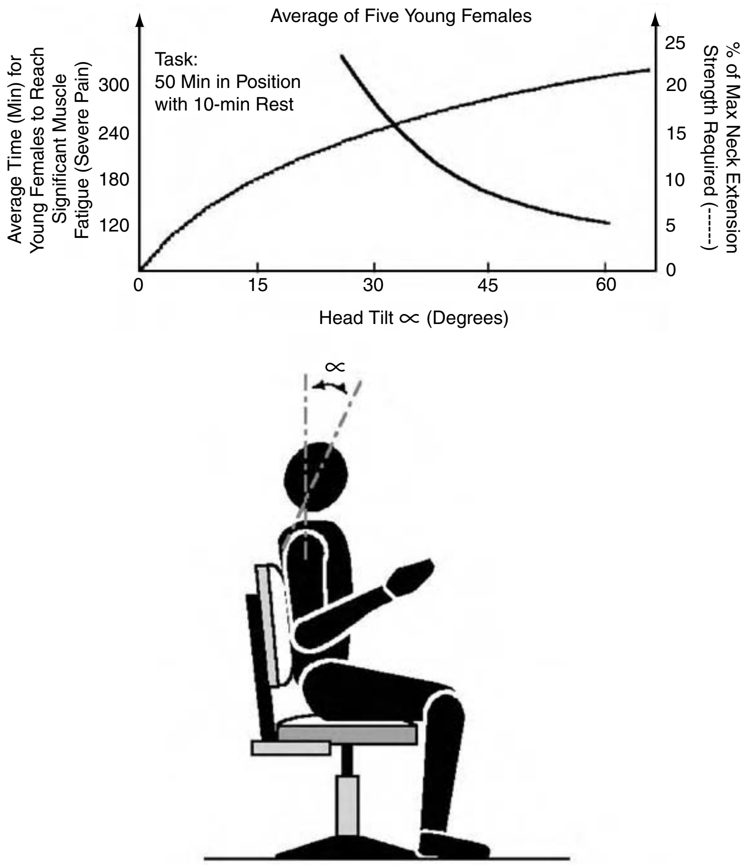

FIGURE 11.16 Neck extensor fatigue and muscle strength required versus head tilt angle. (Adapted from Chaffin, D.B. and Andersson, G.B., *Occupational Biomechanics*, John Wiley & Sons, Inc., New York, 1991. With permission.)

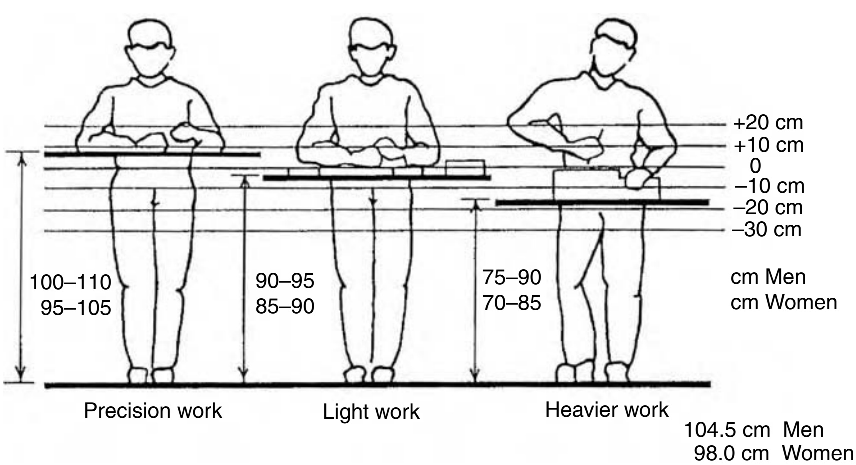

FIGURE 11.17 Recommended heights of bench for standing work. The reference line (+0) is the height of the elbows above the floor. (Adapted From Grandjean, E., *Fitting the Task to the Man: An Ergonomic Approach*, Taylor & Francis, Ltd., London, 1982. With permission.)

this type of work are often minimal. Thus, shoulder position represents a higher priority in the hierarchy of task needs in this situation. In this situation, ideal neck posture is typically sacrificed in favor of more favorable shoulder and arm postures. For this reason, heavy work is performed at a height of 70 to 90 cm above floor level. With the work set at this height, the position wherein the elbows are close to 90° maximizes strength (Figure 11.6). In addition, the shoulders are close to 30° of abduction, which minimizes fatigue. In this situation, the neck is not in an optimal position but the hierarchy logic dictates that the visual demands of a heavy task would not be substantial and thus the neck would not be flexed for prolonged periods of time and, therefore, do not pose much of a risk.

The third work height situation involves light work. Light work is a mix of moderate visual demands with moderate strength requirements. In this situation, work is a compromise between shoulder position and visual accommodation and neither visual nor strength demands dominate the hierarchy of work needs. Thus, the height of the work is set at a height between those of the precision work height level and the heavy work height level. In this manner, a compromise between the benefits and costs associated with accommodating the neck versus the shoulder is resolved. This situation dictates that the work is performed at a level of between 85 and 95 cm off the floor under light work conditions.

11.3.1.4 The Back

Low back disorders (LBD) have been identified as one of the most common and significant musculoskeletal problems in the U.S. that results in substantial amounts of morbidity, disability, and economic loss (Hollbrook et al., 1984; Praemer et al., 1992). LBD are one of the most common reasons for workers to miss work. Back disorders were responsible for the loss of over 100 million lost workdays in 1988 with 22 million cases reported that year (Guo, 1993; Guo et al., 1999). Among those under 45 years of age, LBD is the leading cause of activity limitations and can affect upto 47% of workers with physically demanding jobs (Andersson, 1997). The prevalence of LBD has also been observed to increase by 2700% since 1980 (Pope, 1993). The costs associated with LBD are significant with health care expenditures incurred by individuals with back pain in the U.S. exceeding $90 billion in 1998 (Luo et al., 2004).

It is clear that the risk of LBD can be associated with industrial work (NRC, 1999, 2001). Thirty percent of occupation injuries in the U.S. are caused by overexertion, lifting, throwing, holding, carrying, pushing, and or pulling objects that weigh 50 lb or less. Twenty percent of all workplace injuries and illnesses are back injuries, which account for upto 40% of compensation costs. Estimates of occupational LBD prevalence vary from 1 to 15% annually depending upon occupation and, over a career, can seriously affect 56% of workers.

Manual materials handling (MMH) activities, specifically lifting, dominate occupationally related LBD risk. It has been estimated that lifting and MMH account for upto two-thirds of work-related back injuries (NRC, 2001). From a biomechanical standpoint, we assume that most serious and costly back pain is discogenic in nature and has a mechanical origin (Nachemson, 1975). Studies have found increased degeneration in the spines of cadaver specimens who had previously been exposed to physically heavy work (Videman, et al., 1990). This suggests that occupationally related LBDs are closely associated with spine loading.

11.3.1.4.1 Significance of Moments

The most important concept associated with occupationally related LBD risk is that of the external moments imposed about the spine (Marras et al., 1993, 1995). As with most structures, the loading of the trunk is influenced greatly by the external moment imposed about the spine. However, because of the geometric arrangement of the trunk musculature relative to the trunk fulcrum during lifting, very large loads can be generated by the muscles and imposed upon the spine. Figure 11.18 shows this biomechanical arrangement of lever system. As indicated here, the back musculature is at a severe biomechanical disadvantage in many manual materials handling situations. Supporting an external load of 222 N (about 50 lb) at a distance of 1 m from the spine imposes a 222 Nm external moment about the spine. However, since the spine supporting musculature are at a relatively close proximity relative to the external load, the trunk musculature must exert extremely large forces (4440 N or 998 lb) to simply hold the external load in equilibrium. These internal loads can be far greater if dynamic

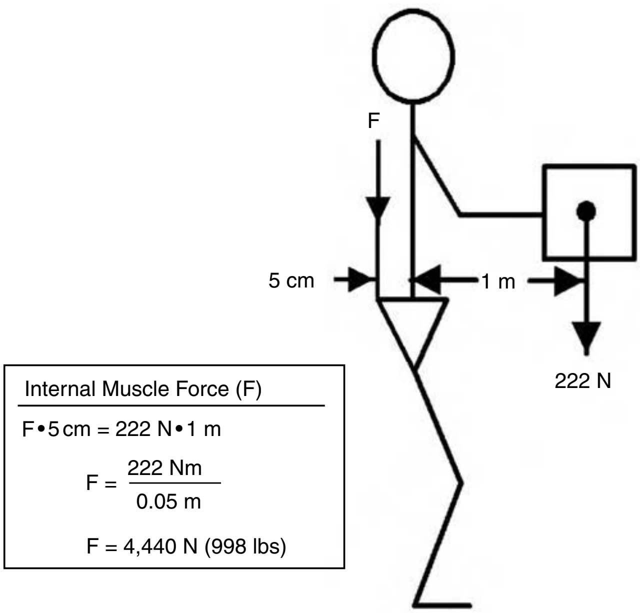

FIGURE 11.18 Internal muscle force required to counterbalance an external load during lifting.

motion of the body is considered (since force is a product of mass and acceleration). Thus, the most important concept to consider in workplace design from a back protection standpoint is to keep the moment arm at a minimum.

11.3.1.4.2 Lifting Style

The external moment concept has major implications for lifting styles or the best "way" to lift. Since the externally applied moment significantly influences the internal loading, the lifting style is of far less concern compared to the magnitude of the applied moment. Some have suggested that proper lifting involves lifting by "using the legs" as opposed to "stoop" lifting (bending from the waist). However, spine loading has also been found to be a function of anthropometry as well as lifting style. Biomechanical analyses (Park and Chaffin, 1974; van Dieen et al., 1999) have demonstrated that no one lift style is correct for all body types. For this reason the National Institute of Occupational Safety and Health (NIOSH, 1981) has concluded that liftstyle need not be a consideration when assessing the risk of occupationally related LBD. Some have suggested that the internal moment of the trunk has a greater mechanical advantage when lumbar lordosis is preserved during the lift (NIOSH, 1981; Anderson et al., 1985; McGill et al., 2000; McGill, 2002a,b). Thus, from a biomechanical standpoint, the primary indicator of spine loading and, thus, the correct lifting style is whatever style permits the worker to bring the center of mass of the load as close to the spine as possible.

11.3.1.4.3 Seated vs Standing Workplaces

Seated workplaces have become more prominent of late, especially with the aging of the workforce and the introduction of service-oriented and data processing jobs. It has been well documented that loads on the lumbar spine are always greater when one is seated compared to a standing posture (Andersson et al., 1975). This is due to the tendency for the posterior (bony) elements of the spine to form an active load path when one is standing. When seated, these elements are disengaged and more of the load passes through the intervertebral disc. Thus, work performed in a seated position puts the worker at greater risk of loading and therefore damaging the disc. Given this situation, it is important to consider the design features of a chair since it may be possible to influence disc loading through chair design. Figure 11.19 shows the results of pressure measurements made in the intervetebral disc of workers as

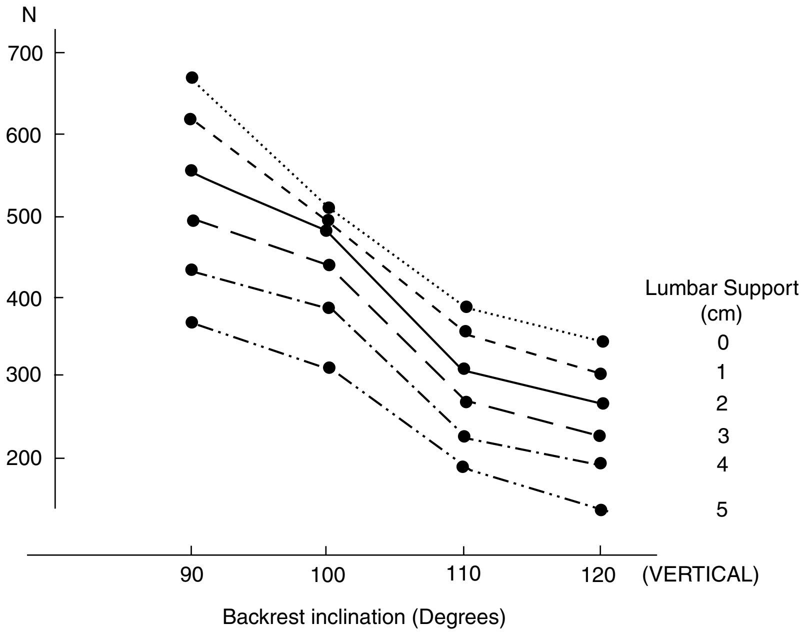

FIGURE 11.19 Disc pressures measured with different backrest inclinations and different size lumbar supports. (Adapted from Chaffin, D.B. and Andersson, G.B., *Occupational Biomechanics*, John Wiley & Sons, Inc., New York, 1991. With permission.)

the back angle of the chair and magnitude of lumbar support are varied. Since it is infeasible to directly measure the forces in the spine *in vivo*, disc pressure measures have traditionally been used as a rough approximation of loads imposed upon the spine. This figure indicates that both the seat back angle and lumbar support features have a significant effect on disc pressure. Disc pressure is observed to decrease as the backrest angle is increased. However, increasing the backrest angle in the workplace is often not practical, since it also has the effect of moving the worker away from the work and thereby increasing external moment. The figure also indicates that increasing lumbar support can also significantly reduce disc pressure. This reduction in pressure is most likely due to the fact that as lumbar curvature (lordosis) is reestablished (with lumbar support) the posterior elements play more of a role in providing an alternative load path as is the case when standing in the upright position.

Less is known about risk to the low back associated with prolonged standing. It is known that the muscles experience low level static exertions and may be subject to the static overload through the muscle static fatigue process described in Figure 11.9. This fatigue can result in lowered muscle force generation capacity and can, thus, initiate the cumulative trauma sequence of events (Figure 11.3). It has been demonstrated that this fatigue and cumulative trauma sequence can be minimized by two actions. First, foot rails provide a mechanism to allow relaxation of the large back muscles and thus increased blood flow to the muscle. This reduces the static load and fatigue in the muscle by the process described in Figure 11.9. When a leg is lifted and rested on the foot rest the large back muscles are relaxed on one side of the body and the muscle can be supplied with oxygen. Alternating legs on the foot rest provides a mechanism to minimize back muscle fatigue throughout the day. Second, floor mats have been shown to decrease the fatigue in the back muscles provided that the mats have proper compression characteristics (Kim et al., 1994). Floor mats are believed to induce body sway, which facilitate the pumping of blood through back muscles, thereby, minimizing fatigue.

Our knowledge of when standing workplaces are preferable is dictated mainly by work performance criteria. In general, standing workplaces are preferred when: (1) the task required a high degree of mobility (reaching and monitoring in positions that exceed the reach envelope or when performing tasks at different heights or different locations), (2) precise manual control actions are not required, (3) leg room is not available (when leg room is not available, the moment arm distance between the external load and the back is increased and thus greater internal back muscle force and spinal load result), and (4) heavy weights are handled or large forces are applied. When jobs must accommodate both sitting and standing, it is important to ensure that the positions and orientations of the body, especially the upper extremity, are in the same location under both standing and sitting conditions.

11.3.1.5 Wrists

The wrist has been of increased interest to ergonomists in the past three decades. The Bureau of Labor Statistics reports that repetitive trauma has increase from 18% of occupational illnesses in 1981 to 63% of occupational illnesses in 1993. Based upon these figures, repetitive trauma has been described as the *fastest growing* occupational problem. Even though these numbers and statements appear alarming one must acknowledge that occupational illnesses represent 6% of all occupational injuries and illnesses. Furthermore, these figures for illness include illnesses unrelated to musculoskeletal disorders such as noise-induced hearing loss. Thus, the magnitude of the cumulative trauma problem must not be overstated. Nonetheless, there are specific industries (i.e., meat packing, poultry processing, etc.) where cumulative trauma to the wrist is a major problem and this problem has reached epidemic proportions within these industries.

11.3.1.5.1 Wrist Anatomy and Loading

In order to understand the biomechanics of the wrist and how cumulative trauma occurs in this structure one must appreciate the anatomy of the upper extremity. Figure 11.20 shows a simplified anatomical drawing of the wrist. This figure shows that few power-producing muscles reside in the hand itself. The thenar muscle, which activates the thumb is one of the few power producing muscles in the hand. The vast majority of the hand's power-producing muscles are located in the forearm. Force is transmitted from these forearm muscles to the fingers through a network of tendons (tendons attach muscles to bone). These tendons originate at the muscles in the forearm traverse the wrist (with many of them passing through the carpal canal), pass through the hand, and culminate at the fingers. These tendons are secured or "strapped down" at various points along this path with ligaments that keep the tendons in close proximity to the bones forming a sort of pulley system. This system results in a hand that is very small and compact, yet capable of generating large amounts of force. The price the musculoskeletal system pays for this design is friction. The forearm muscles must transmit force over a very long distance in order to supply internal forces to the fingers. Thus, a great deal of tendon travel must occur and this tendon travel can result in significant tendon friction under repetitive motion conditions thereby initiating the events outlined in Figure 11.3. Thus, the key to controlling wrist cumulative trauma is rooted in an understanding of those workplace factors that adversely affect the internal force generating (muscles) and transmitting (tendons) structures.

11.3.1.5.2 Biomechanical Risk Factors for the Wrist

A number of risk factors for wrist cumulative trauma have been documented in the literature. First, deviated wrist postures are known to reduce the volume of the carpal tunnel and, thus, increase tendon friction. In addition, grip strength is dramatically reduced by deviations in the wrist posture. Figure 11.21 indicates that any deviation from the wrist's neutral position significantly decreases the grip strength of the hand. This reduction in strength is caused by a change in the length–strength relationship (Figure 11.5) of the forearm muscles once the wrist is bent. Hence, the muscles are working at a level that is greater than necessary. This reduced strength potential associated with deviated wrist positions can, therefore, more easily initiate the sequence of events associated with cumulative trauma (Figure 11.3). Thus, deviated wrist postures not only increase tendon travel and friction, but also increase the amount of muscle strength necessary to perform the gripping task.

Second, increased frequency or repetition of the work cycle has been identified as a risk factor for cumulative trauma disorders (CTD; Silverstein et al., 1996, 1997). Studies have indicated that increased frequency of wrist motions increases the risk of developing a cumulative trauma disorder. Repeated

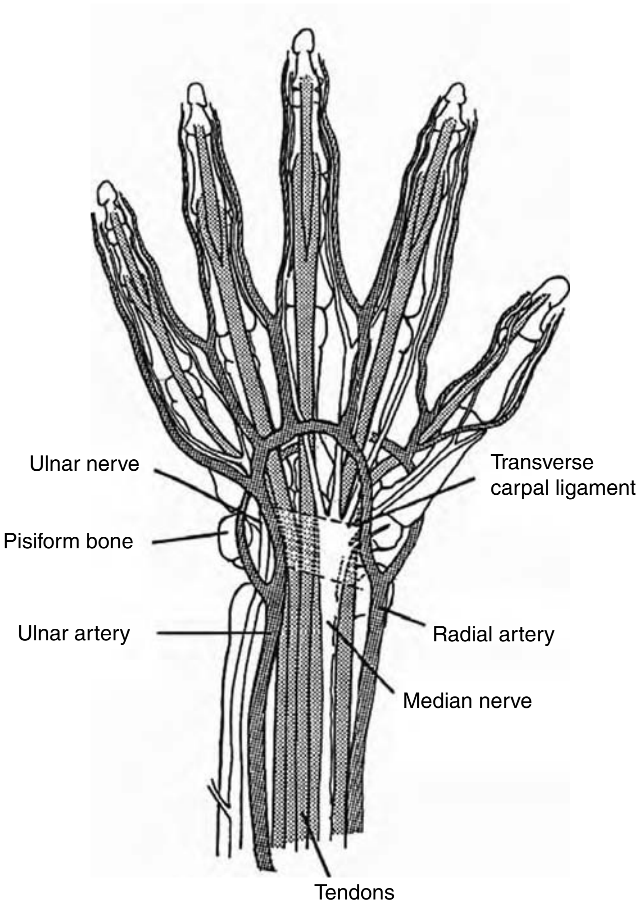

FIGURE 11.20 Important anatomical structures in the wrist.

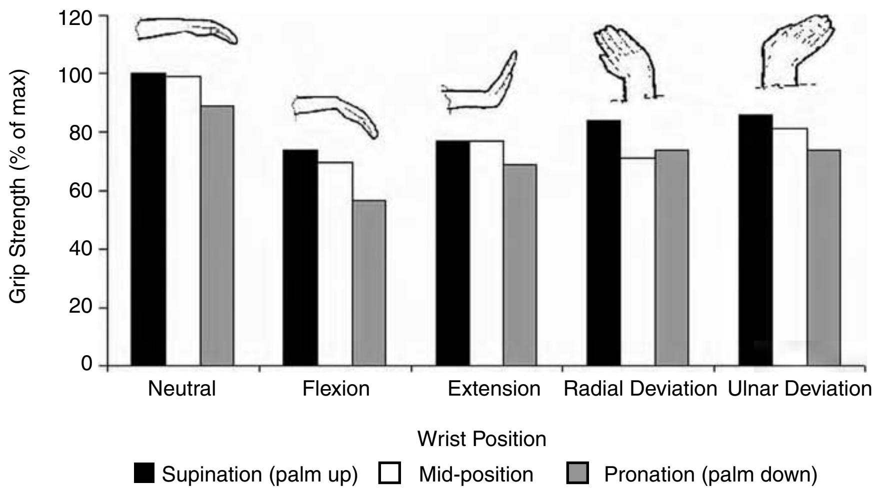

FIGURE 11.21 Grip strength as a function of wrist and forearm position. (Adapted from Sanders, M.S. and McCormick, E.F., *Human Factors in Engineering and Design*, McGraw-Hill Inc., New York, 1993. With permission.)

motions requiring a cycle time of less than 30 sec is considered a candidate for cumulative trauma disorder risk.

Third, the force applied by the hands and fingers during a work cycle has been identified as a risk factor. In general, the greater the force required by the work the greater the risk of CTD. Greater hand forces result in greater tension within the tendons and result in greater tendon friction and tendon travel. Another factor related to force is wrist acceleration. Industrial surveillance studies have reported that repetitive jobs resulting in greater wrist acceleration are associated with greater CTD incident rates (Marras and Schoenmarklin, 1993; Schoenmarklin et al., 1994). Since force is a product of mass and acceleration, jobs that increase the angular acceleration of the wrist joint result in greater tension and force transmitted through the tendons. Thus, wrist acceleration can be another mechanism of imposing force on the wrist structures.

Fourth, as shown in Figure 11.20, the anatomy of the hand is such that the median nerve becomes very superficial at the palm. Direct impact to the palm of the hand through pounding or striking an object with the palm, as is done often in assembly work, can directly stimulate the median nerve and initiate symptoms of cumulative trauma even though the work may not be repetitive.

11.3.1.5.3 Grip Design

The design of a tool's gripping surface can dramatically affect the activity of the internal force transmission system (tendon travel and tension). The grip opening and shape have a major influence on the available grip strength. Figure 11.22 shows how grip strength capacity changes as a function of the separation distance of the grip opening. This figure indicates that maximum grip strength occurs within a very narrow range of grip openings. If the grip opening deviates from this ideal range by as little an inch (a couple of centimeters), then grip strength is dramatically reduced. This change in strength is also due to the length–strength relationship of the forearm muscles. Also indicted in Figure 11.22 are the effects of hand anthropometry. The workers hand size as well as hand preference

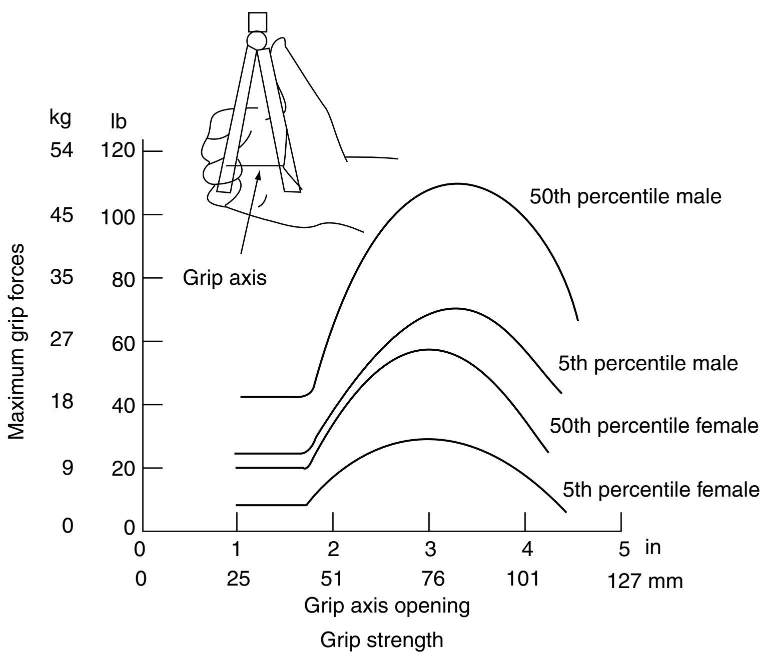

FIGURE 11.22 Grip strength as a function of grip opening and hand anthropometry. (Adapted from Sanders, M.S. and McCormick, E.J., *Human Factors in Engineering and Design*, McGraw-Hill Inc., New York, 1993. With permission.)

can influence grip strength and risk. Therefore, proper design of the handles is crucial in ergonomic workplace design.

Handle shape can also affect the strength of the wrist. Figure 11.23 shows how changes in the design of screwdriver handles can affect the maximum force that can be exerted. The biomechanical origin of these differences in strength capacity is most likely related to the length–strength relationship of the forearm muscles as well as contact area with the tool. The handle designs that result in less strength permit the wrist to twist or permit the grip to slip resulting in a deviation from the ideal length–strength position in the forearm muscles.

11.3.1.5.4 Gloves

The use of gloves can significantly influence the generation of grip strength and may play a role in the development of CTDs. When gloves are worn during work three effects must be considered. First, the grip strength generated is often reduced. There is typically a 10 to 20% reduction in grip strength when gloves are worn. When using gloves the coefficient of friction between the hand and the tool can be reduced which, in turn, permits some slippage of the hand upon the tool surface. This slippage can result in a deviation from the ideal muscle length and thus a reduction in available strength. The degree of slippage and the degree of strength loss depends upon how well the gloves fit the hand and the type of material used in the glove. Poorly fitting gloves result in greater strength loss. Figure 11.24 indicates how the glove material and glove fit can dramatically influence grip force application.

Second, when wearing gloves, even though the externally applied force (grip strength) is often reduced, the internal forces are often very large compared to not using a glove. For a given grip strength the muscle activity is significantly greater when using gloves compared to a bare-handed condition (Kovacs et al., 2002). Thus, the musculoskeletal system is less efficient when wearing a glove.

Third, the ability to perform a work task is affected negatively when wearing gloves. Figure 11.25 shows the increase in time required to perform work tasks when wearing gloves composed of different materials compared to performing the task bare-handed. The figure indicates that task performance can increase upto 70% when wearing gloves.

These effects have indicated that there are biomechanical costs associated with glove usage. Less strength capacity is available to the worker, more internal force is generated, and worker productivity is affected. These negative effects of gloves do not mean that gloves should never be worn at work. When hand protection is needed gloves should be considered as a potential solution. However, protection should only be provided to the parts of the hand that require protection. For example, if the palm of the hand requires protection, fingerless gloves might provide an acceptable solution. If the fingers require protection, but there is little risk to the palm of the hand, then grip tape wrapped around the fingers might be considered. In addition, different styles, materials, and sizes of gloves will fit workers differently. Thus, gloves produced by various manufacturers and of different sizes should be available to the worker to minimize the negative effects mentioned before.

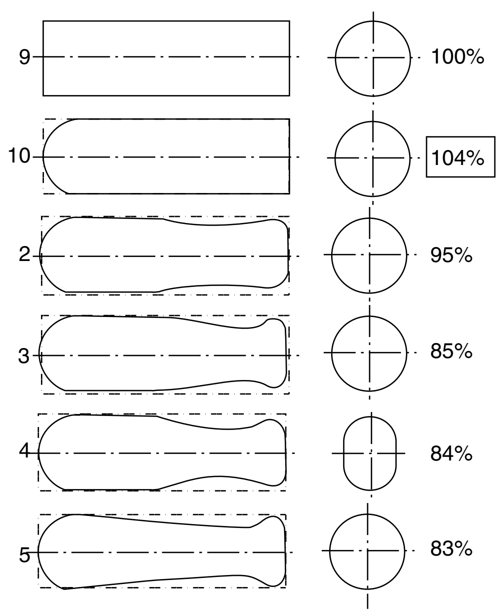

FIGURE 11.23 Maximum force, which could be exerted on a screwdriver as a function of handle shape. (From Konz, S.A., *Work Design: Industrial Ergonomics*, 2nd ed., Grid Publishing, Inc., Columbus, OH, 1983. With permission.)

11.3.1.5.5 Design Guidelines

This discussion has indicated that there are many factors that can affect the biomechanics of the

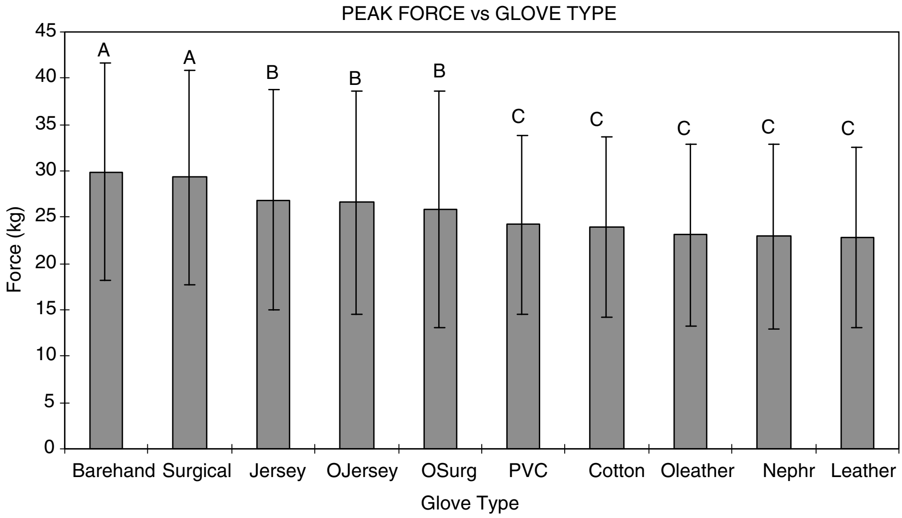

FIGURE 11.24 Peak grip force shown as a function of type of glove. Different letters above the columns indicate statistically significant differences.

wrist and the subsequent risk of CTDs. This suggests that proper ergonomic design of a work task cannot be accomplished by simply providing the worker with an "ergonomically designed" tool. Since ergonomics is associated with matching the workplace design to the workers' capabilities it is not possible to design an "ergonomic tool" without considering the workplace design and task requirements simultaneously. What might be an "ergonomic" tool for one work situation may be improper for use while a worker is assuming another work posture. For example, using an *in-line* tool may keep the wrist straight when inserting a bolt into a horizontal surface. However, if the bolt is to be inserted into a vertical surface a *pistol grip* tool may be more appropriate. Using the in-line tool in this situation (inserting a bolt into a vertical surface) may cause the wrist to be significantly deviated. Hence, there are no ergonomic tools.

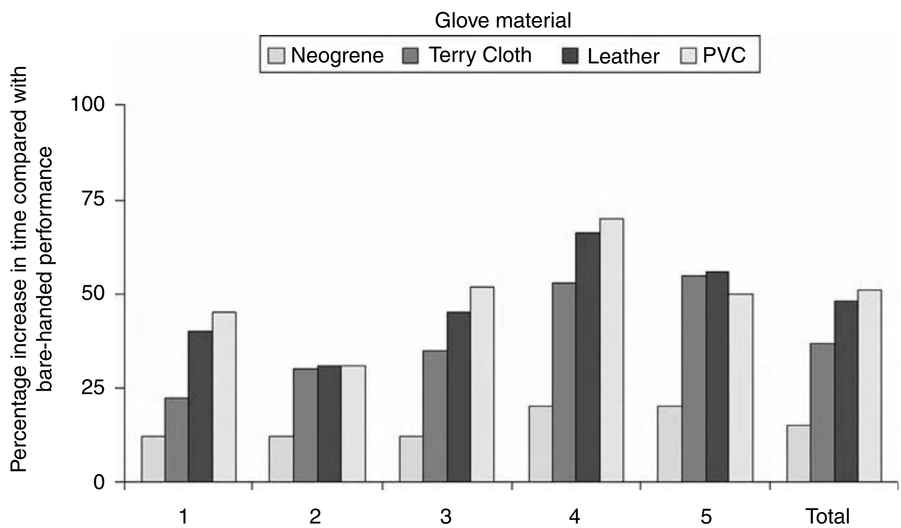

FIGURE 11.25 Performance (time to complete) on a maintenance-type task while wearing gloves constructed of five different materials. (From Sanders, M.S. and McCormick, E.J., *Human Factors in Engineering and Design*, McGraw-Hill Inc., New York, 1993. With permission.)

There are just ergonomic *situations.* What may be an ergonomically correct tool in one situation may not be ergonomically correct in another work situation.

Workplace design should be performed with care and trade-offs between different parts of the body must be considered by taking into consideration the various biomechanical trade-offs. Given these considerations, the following components of the workplace should be considered when designing a workplace so that cumulative trauma risk is minimized. First, maintain a neutral wrist posture. Second, minimize tissue compression. Third, avoid actions that repeatedly impose force on the internal structures. Fourth, minimize required wrist accelerations and motions. Fifth, consider the impact of glove use, hand size, and left-handed workers.

11.4 Analysis and Control Measures Used in the Workplace

Several analyses and control measures have been developed to evaluate and control biomechanical loading of the body during work. Since LBDs are often the objective of a biomechanical workplace analysis, most of these analyses methods have focused on spine risk. However, several of the measures also include analyses of risk to other body parts.

11.4.1 Lifting Belts

Back support belts or lifting belts have been used with increasing frequency in the workplace. However, a review of the literature related to lifting belts offers no clear biomechanical benefits of belt use. Reviews by McGill (1993) and NIOSH (1994) had concluded that there are so few well-executed studies that one can not unequivocally judge the benefits of lifting belts. However, later epidemiologic studies have indicated that there are few benefits to back belt usage for those not suffering from an LBD (Wassell et al., 2000).

Epidemiological studies have generally been limited in scope and often result in findings that were confounded by other factors such as training, the type of belt used, or the "Hawthorne Effect." Walsh and Schwartz (1990) reported a reduction in LBD injury rate with the usage of back supports (hard shell corsets) and have recommended that they would be effective at controlling the risk of LBD. However, the data from this study suggest that back supports were only effective for those workers who had previously suffered an LBD. Mitchell et al. (1994) retrospectively evaluated injury data associated with belt use over a 6-yr period at Tinker Air Force Base. Over this time period, two different types of belts were used. Leather belts were used in the first two years of the study, whereas, velcro belts were used over the last four years. No relationship between belt usage and back injury could be established, but they did find that those who wore belts suffered more costly injuries once they occurred. Reddell et al. (1992) observed that when workers stopped wearing belts the risk of injury increased. However, this study suffers from small sample size, which makes it difficult to assess the strength of the association.

Psychophysical studies (which can be used to define tolerance) have attempted to assess whether the magnitude of the weight a person was willing to lift changes when wearing a back belt. McCoy et al. (1988) found that subjects were willing to lift 19% more weight when belts were used but found no difference between belt types. Subjects reported that they preferred the elastic belt. However, this does not suggest that workers would be at lowered risk of back injury since it is not clear that spine tolerance to load would be increased with belt use.

Biomechanically based studies of lifting belts have documented their influence upon trunk motion, trunk muscle activity, and indirect indicators or predictions of trunk loading. The most consistent finding of these studies is that lateral bending and twisting trunk motion is significantly reduced with belt usage (Lantz and Schultz, 1986; McGill et al., 1994; Lavender et al., 1995). However, belt use has not resulted in a reduction of spine loading under realistic materials handling conditions (Granata et al., 1997; Marras et al., 2000a, b).

Perhaps the most important reason to be cautious of lifting belts is unrelated to biomechanical loading of the spine. There appear to be physiological reasons to be concerned with the use of lifting belts. One study has shown that lifting belts can significantly increase blood pressure (Rafacz and McGill, 1996). This could become problematic for workers who have a compromised cardiovascular system.

The brief review indicates that there is a large amount of conflicting evidence as to the benefits or liabilities associated with the use of back belts. There appears to be little biomechanical benefit to belt usage and some negative physiological consequences. Recent epidemiologic studies have not been able to find any evidence of benefit. A consistent finding among the studies is that if there is a benefit to back belts, it is probably for those who have previously experienced an LBD. The literature also suggests that belts should only be used for a limited period of time. Until more definitive studies are available it is prudent to use caution when recommending the use of back belts in a work environment. This includes a screening by an occupational physician who is familiar with the literature so that potential cardiovascular problems can be assessed.

11.4.2 1981 NIOSH Lifting Guide

The NIOSH has developed two assessment tools or guides to help determine whether a manual materials handling task is safe or risky. The lifting guide was originally developed in 1981 (NIOSH, 1981) and applies to lifting situations where the lifts are performed in the sagittal plane and to motions that are slow and smooth. Two benchmarks or limits are defined by this guide. The first limit is called the *action limit* (AL) and represents a magnitude of weight in a given lifting situation, which would impose a spine load corresponding to the beginning of LBD risk along a risk continuum. The AL is associated with the point in Figure 11.10 at which people under 40 yr of age just begin to experience a risk of vertebral endplate microfracture (3400 N of compressive load). The guide estimates the force imposed upon the spine of a worker as a result of lifting a weight and compares this spine load to the AL. If the weight of the object results in a spine load that is below the AL, the job is considered safe. If the weight lifted by the worker is larger than the AL, there is at least some level of risk associated with the task. The general form of the AL is defined according to Equation (11.1).

$$\text{AL} = k(HF)(VF)(DF)(FF), \tag{11.1}$$

where AL is the action limit in kg or lb; k is the load constant (40 kg or 90 lb), which is the greatest weight a subject could lift if all lifting conditions are optimal; *HF* is the horizontal factor defined as the horizontal distance from a point bisecting the ankles to the center of gravity of the load at the lift origin. Defined algebraically as $15/H$ (metric) or $6/H$ (US units); *VF* is the vertical factor or height of the load at lift origin. Defined algebraically as $(0.004)\ |V - 75|$(metric) or $1\text{-}(0.01)|V - 30|$(US units); *DF* is the distance factor or the vertical travel distance of the load. Defined algebraically as $0.7 + 7.5/D$ (metric) or $0.7 + 3/D$ (US units); *FF* is the frequency factor or lifting rate defined algebraically as $1 - F/F_{\text{max}}$ $F =$ average frequency of lift, F_{max} is shown in Table 11.3.

The logic associated with this equation assumes that if the lifting conditions are ideal a worker could safely hold (and implies lift) the load constant, k (40 kg or 90 lb). If the lifting conditions are not ideal the allowable weight is discounted according to the four factors *HF, VF, DF,* and *FF.* These four factors are shown in monogram form in Figure 11.26 through Figure 11.29. According to the load discounting

TABLE 11.3 F_{max} Table

	Average Vertical Location (cm) (in)	
Period	Standing $V > 75$ (3)	Stooped $V \leq 75$ (3)
1 h	18	15
8 h	15	12

Source: Reprinted from NIOSH, *Work Practices Guide for Manual Lifting*, Department of Health and Human Services (DHHS) NIOSH, Cincinnati, OH, 81–122, 1981. With permission.

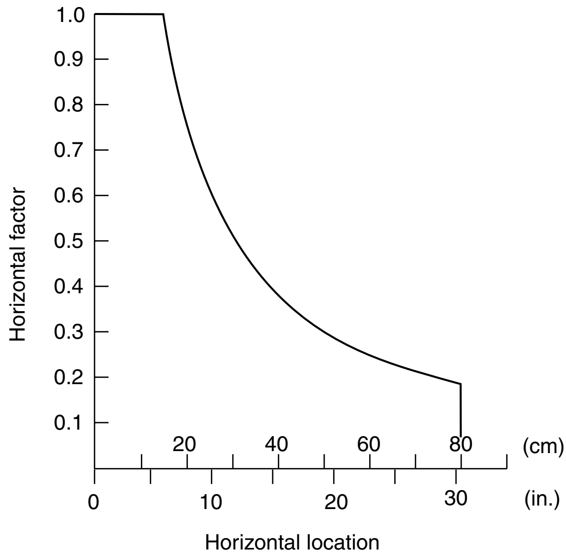

FIGURE 11.26 Horizontal factor, (*HF*) varies between the body interference limit and the limit of functional reach. (Adapted from National Institute for Occupational Safety and Health (NIOSH), Work practices guide for manual lifting, Department of Health and Human Services (DHHS), NIOSH, Cincinnati, OH, No. 81–122, 1981. With permission.)

associated with these figures, the *HF*, which is associated with the external moment has the most dramatic effect on acceptable lifting conditions. *VF* and *DF* are associated with the back muscle's length–strength relationship. *FF* attempts to account for the cumulative effects of repetitive lifting.

The second benchmark associated with this guide is the *maximum permissible limit* or MPL. The MPL represents the point at which significant risk, defined in part, as a significant risk of vertebral endplate microfracture (Figure 11.10). The MPL is associated with a compressive load on the spine of 6400 N, which corresponds to a point at which 50% of the people would be expected to suffer a vertebral endplate

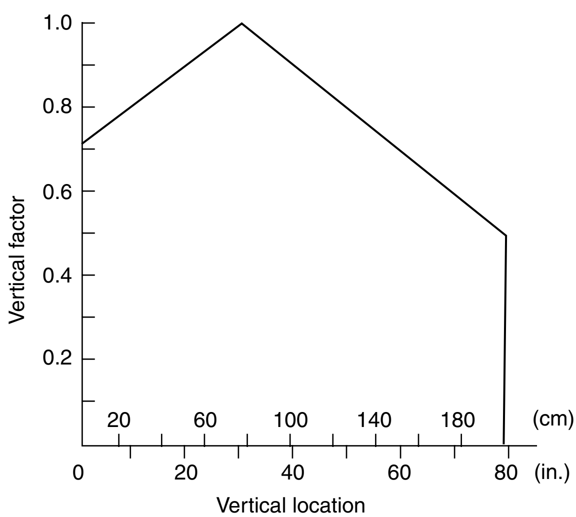

FIGURE 11.27 Vertical factor, (*VF*) varies both ways from knuckle height. (Adapted from National Institute for Occupational Safety and Health (NIOSH), Work practices guide for material lifting, Department of Health and Human Services (DHHS), NIOSH, Cincinnati, OH, 81–122, 1981. With permission.)

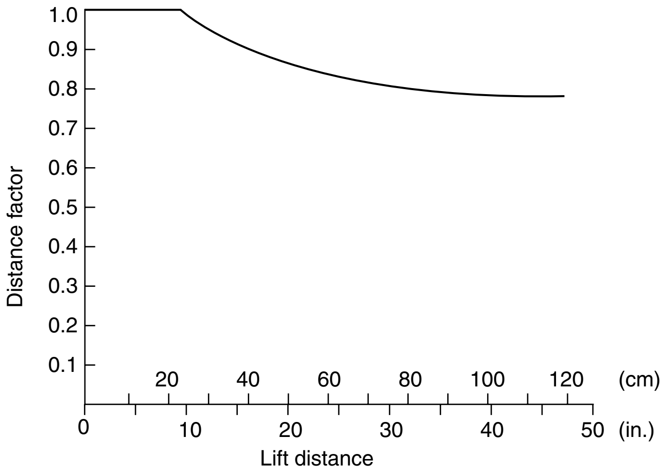

FIGURE 11.28 Distance factor, (*DF*) varies between a minimum vertical distance of 25 cm (10 in.) that was moved to a maximum distance of 200 cm (80 in.). (Adapted from National Institute for Occupational Safety and Health (NIOSH), Work practices guide for manual lifting. Department of Health and Human Services (DHHS), National Institute for Occupational Safety and Health (NIOSH), Cincinnati, OH, 81–122, 1981. With permission.)

microfracture. Equation (11.2) indicates that the MPL is a function of the AL and is defined as follows:

$$\text{MPL} = 3(\text{AL}). \tag{11.2}$$

The weight that the worker expected to lift in a work situation is compared to the AL and MPL. If the magnitude of weight falls below the AL the work is considered safe and no adjustments are necessary. If the magnitude of the weight falls above the MPL then the work is considered risky and engineering changes involving the adjustment of *HF*, *VF*, and/or *DF* are required to reduce the AL and MPL. If the weight falls between the AL and MPL then either engineering changes or administrative changes, defined as selecting workers who are less likely to be injured or rotating workers, are recommended.

The AL and MPL were also indexed to nonbiomechanical benchmarks. According to NIOSH (1981) these limits also correspond to strength, energy expenditure, and psychophysical acceptance points.

11.4.3 1993 Revised NIOSH Equation

The 1993 NIOSH revised lifting equation was introduced in order to address those lifting jobs that violate the sagittally symmetric lifting assumption (Waters et al., 1993). The concept of AL and MPL was replaced with a concept of a *lifting index* or *LI*. The *LI* is defined in Equation (11.3).

$$LI = \frac{L}{\text{RWL}}, \tag{11.3}$$

where *L* is the load weight or the weight of the object to be lifted; RWL is the recommended weight limit for the particular lifting situation; *LI* is the lifting index used to estimate relative magnitude of physical stress for a particular job.

If the *LI* is greater than 1.0, an increased risk for suffering a lifting-related LBD exists. The RWL is similar to the 1981 lifting guide AL equation [Equation (11.1)] in that it contains factors that discount the allowable load according to the horizontal distance, vertical location of the load, vertical travel distance, and frequency of lift. However, the form of these discounting factors was changed. Moreover, two additional discounting factors have been included. These additional factors include a lift asymmetry factor to account for asymmetric lifting conditions and a coupling factor that accounts for whether or not the load lifted has handles. The RWL is represented algebraically in Equation (11.4) (metric units) and Equation (11.5) (US units).

$$\text{RWL (kg)} = 23(25/H)[1 - (0.003|V - 75|)](0.82 + 4.5/D)(FM)[1 - (0.0032A)](CM), \quad (11.4)$$

$$\text{RWL (lb)} = 51(10/H)[1 - (0.0075|V - 30|)](0.82 + 1.8/D)(FM)[1 - (0.0032A)](CM), \quad (11.5)$$

where H is the horizontal location forward of the midpoint between the ankles at the origin of the lift. If significant control is required at the destination then H should be measured both at the origin and destination of the lift; V is the vertical location at the origin of the lift; D is the vertical travel distance between origin and destination of the lift; FM is the frequency multiplier shown in Table 11.4; A is the angle between the midpoint of the ankles and the midpoint between the hands at the origin of the lift; CM is the coupling multiplier ranked as either food, fair, or poor as described in Table 11.5.

In this revised equation the load constant has been significantly reduced compared to the 1981 equation. The adjustments for load moment, muscle length–strength relationships, and cumulative loading are still integral parts of this equation. However, these adjustments or discounting factors have been changed (compared to the 1981 Guide) to reflect the most conservative value of the biomechanical, physiological, psychophysical, or strength data upon which they are based. Recent studies report that the 1993 revised equation yields a more conservative (protective) prediction of work-related LBD risk (Marras et al., 1999).

11.4.4 Static Models

Biomechanically based spine models have been developed to help assess occupationally related manual materials handling tasks. These models assess the task based upon both spine loading criteria as well as through an evaluation of the strength required at the various major body joints in order to perform the task. One of the early static assessment models was developed by Chaffin at the University of Michigan (Chaffin, 1969). This original two-dimensional (2D) model has been expanded to a three-dimensional (3D) static model (Chaffin and Muzaffer, 1991; Chaffin et al., 1999) and has been developed to help

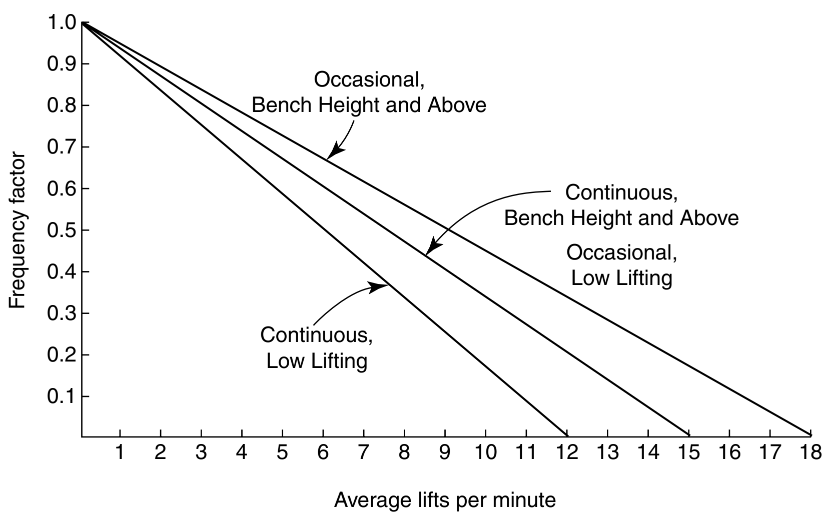

FIGURE 11.29 Frequency factor (*FF*) varies with lifts/minute and the F_{max} curve. The F_{max} depends upon lifting posture and lifting time. (Adapted from National Institute for Occupational Safety and Health (NIOSH), Work practices guide for manual lifting. Department of Health and Human Services (DHHS), National Institute for Occupational Safety and Health (NIOSH), Cincinnati, OH, 81–122, 1981. With permission.)

TABLE 11.4 Frequency Multiplier Table (*FM*)

Frequency Lifts/min(F)[b]	Work Duration ≤ 1 h		> 1 but ≤ 2 h		> 2 but ≤ 8 h	
	$V < 30$[a]	$V \geq 30$	$V < 30$	$V \geq 30$	$V < 30$	$V \geq 30$
≥ 0.2	1.00	1.00	0.95	0.95	0.85	0.85
0.5	0.97	0.97	0.92	0.92	0.81	0.81
1	0.94	0.94	0.88	0.88	0.75	0.75
2	0.91	0.91	0.84	0.84	0.65	0.65
3	0.88	0.88	0.79	0.79	0.55	0.55
4	0.84	0.84	0.72	0.72	0.45	0.45
5	0.80	0.80	0.60	0.60	0.35	0.35
6	0.75	0.75	0.50	0.50	0.27	0.27
7	0.70	0.70	0.42	0.42	0.22	0.22
8	0.60	0.60	0.35	0.35	0.18	0.18
9	0.52	0.52	0.30	0.30	0.00	0.15
10	0.45	0.45	0.26	0.26	0.00	0.13
11	0.41	0.41	0.00	0.23	0.00	0.00
12	0.37	0.37	0.00	0.21	0.00	0.00
13	0.00	0.34	0.00	0.00	0.00	0.00
14	0.00	0.31	0.00	0.00	0.00	0.00
15	0.00	0.28	0.00	0.00	0.00	0.00
>15	0.00	0.00	0.00	0.00	0.00	0.00

[a]Values of V are in inches.
[b]For lifting less frequently than once per 5 min, set $F = 0.2$ lifts/min.
Source: Reprinted from NIOSH, *Applications Manual for the Revised NIOSH Lifting Equation*, Cincinnati, OH, Publication No. 94–122, 1994. With permission.

assess the risk of injury during manual materials handling activities. In both models the moments imposed upon the various joints of the body due to the object lifted are evaluated assuming that a static posture is representative of the instantaneous loading of the body. These models then compare the imposed moments about each joint with the static strength capacity derived from a working population. The static strength capacity of the major articulations (assessed by this model) have been documented in a database of over 3000 workers. In this manner the proportion of the population capable of performing a particular static exertion is predicted. In addition, the joint that limits the capacity to perform the task can be identified via this method. These models assume that a single equivalent muscle (internal force) supports the external moment about each joint. By considering the contribution of the externally applied load and the internally generated single muscle equivalent, spine compression acting on the lumbar discs is predicted. The predicted compression can then be compared to the tolerance limits of the vertebral endplate (Figure 11.10). An important assumption of these models is that no significant motion occurs during the exertion since it is a static model. The implications of these assumptions are discussed further in Chapter 28. Figure 11.30 shows the output screen for this computer model where the lifting posture, lifting distances, strength predictions, and spine compression are shown.

TABLE 11.5 Coupling Multiplier

Coupling Type	Coupling Multiplier $V < 30$ inches (75 cm)	$V \geq 30$ inches (75 cm)
Good	1.00	1.00
Fair	0.95	1.00
Poor	0.90	0.90

Source: Reprinted from NIOSH, *Application Manual for Revised NIOSH Equation*, Cincinnati, OH, Publication No. 94–122, 1994. With permission.

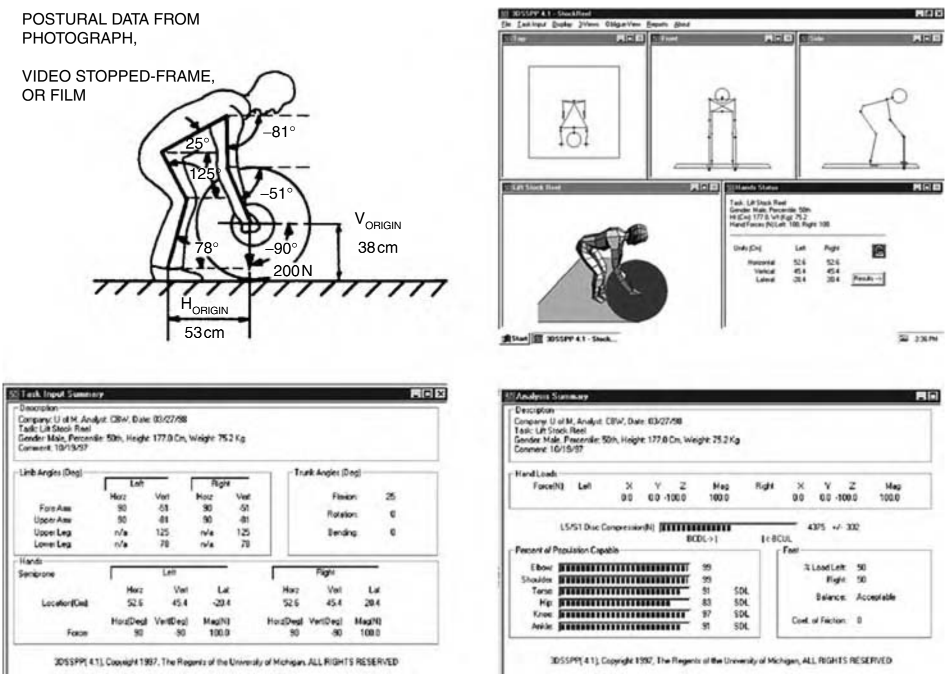

FIGURE 11.30 The 2D-static strength prediction model. (Adapted from Chaffin, D.B. and Andersson, G.B., *Occupational Biomechanics*, John Wiley & Sons, Inc., New York, 1991. With permission.)

11.4.5 Multiple Muscle System Models

One of the significant simplifying assumptions inherent in most static models is that the coactivation of the trunk musculature during a lift is negligible. The trunk is truly a multiple muscle system with many major muscle groups supporting and loading the spine (Schultz and Andersson, 1981). This can be seen in the cross-section of the trunk shown in Figure 11.31. Studies have shown that there is significant coactivation occurring in many of the major muscle groups in the trunk during realistic *dynamic* lifting (Marras and Mirka, 1993). This coactivation is important because all the trunk muscles have the ability to load the spine since antagonist muscles can oppose each other during occupational tasks and increase the total load on the spine. Thus, assumptions regarding single-equivalent muscles within the trunk can lead to erroneous conclusions about spine loading during a task. Studies have indicated that ignoring the coactivation of the trunk muscles during dynamic lifting can misrepresent spine loading by 45 to 70% (Granata and Marras, 1995a; Thelen et al., 1995). In an effort to more accurately estimate the loads on the lumbar spine especially under complex, changing (dynamic) postures multiple muscle system models of the trunk have been developed. Much of the recent research has been focused upon predicting how the multiple trunk muscles coactivate during dynamic lifting.

11.4.5.1 EMG-Assisted Multiple Muscle System Models

People recruit their muscles in various manners when moving dynamically. For example, when moving slowly the agonist muscle may dominate the muscles activities during a lift. However, when moving cautiously, asymmetrically, or rapidly there may be a great deal of antagonistic coactivation present. During occupational lifting tasks these latter dynamic conditions are typically the rule rather than the exception during lifting. As line speeds increase, highly dynamic motions are becoming more common and it is becoming more important to understand the role of muscle coactivation

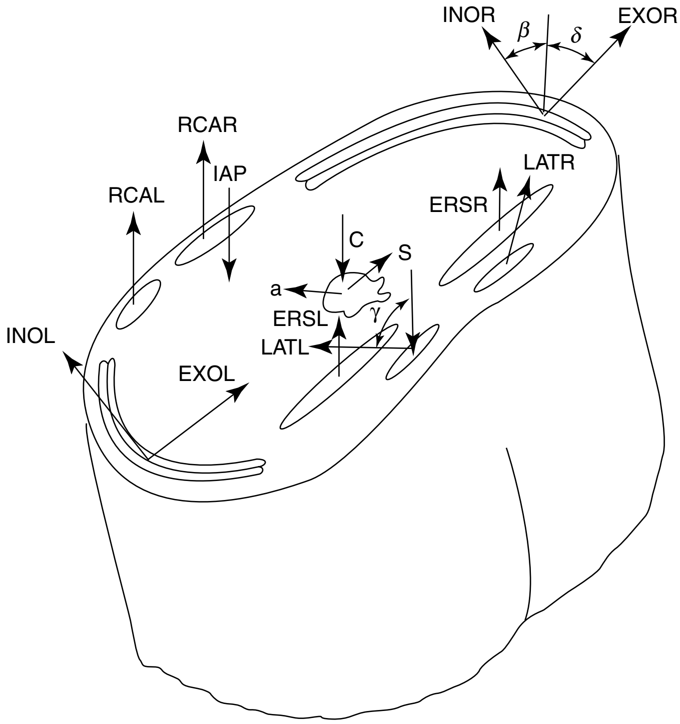

FIGURE 11.31 Cross-sectional view of the human trunk at the lumbrosacral junction. (Adapted from Schultz, A.B. and Andersson, G.B.J., *Spine*, 6, pp. 76–82, 1981. With permission.)

during work. Because of the variability in muscle recruitment patterns it has been virtually impossible to predict the instantaneous coactivation and resultant loading on the spine during dynamic trunk exertions. One of the few means to accurately account for the effect of the trunk muscle system coactivation upon spine loading is through the use of biologically assisted models. The most common of these models are electromyographic or EMG-assisted models. These models take into account the individual recruitment patterns of the muscles during a specific lift for a specific individual. By directly monitoring muscle activity the EMG-assisted model can determine individual muscle force and the subsequent spine loading. These models have been developed and tested under bending and twisting dynamic motion conditions and have been validated (McGill and Norman, 1985, 1986; Marras and Reilly, 1988; Reilly and Marras, 1989; Marras and Sommerich, 1991a, b; Granata and Marras, 1993, 1995b; Marras and Granata, 1995, 1997a, b; Marras et al., 2001). Figure 11.32 shows how such models can assess the effects of lifting dynamics upon spine loading. These models are the only ones that can predict the *multi-dimensional loads* on the lumbar spine under many 3D complex dynamic lifting conditions. The limitation of such models is that they require significant instrumentation of the worker.

11.4.5.2 Stability-Based Models

Efforts have also been attempted to use stability as criteria to govern detailed biologically assisted biomechanical models of the torso (Panjabi, 1992a, b; Cholewicki and McGill, 1996; Solomonow et al., 1999; Cholewicki et al., 2000; Granata and Marras, 2000; Granata and Orishimo, 2001; Granata and Wilson, 2001; Cholewicki and VanVliet, 2002). One potential injury pathway for LBDs suggests that the unnatural rotation of a single spine segment may create loads on passive tissues or other muscle tissues that result in spine injury (McGill, 2002a). Most of the work performed in this area to date has been

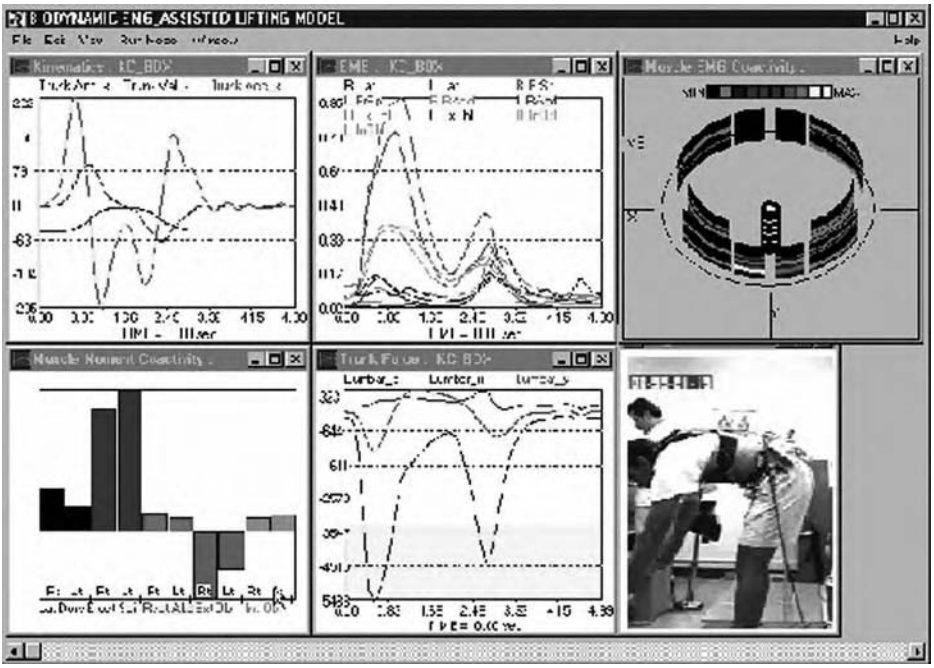

FIGURE 11.32 Windows EMG-assisted model.

directed towards static response of the trunk as well as sudden loading responses (Cholewicki et al., 2000a, b; Granata and Orishimo, 2001; Granata et al., 2001; Granata and Wilson, 2001; Cholewicki and VanVliet, 2002). While these analyses may consider muscle coactivation beneficial from a stability point of view, the point at which the stability benefits of coactivation are overcome by the increased loading remains yet to be determined.

11.4.6 Dynamic Motion and LBD

As discussed throughout this chapter it is clear that dynamic activity may significantly increase the risk of LBD, yet there are few assessment tools available to assess the biomechanical demands associated with workplace dynamics and the risk of LBD. In order to control this biomechanical situation at the worksite, one must know the type of motion that increases biomechanical load and determine "how much motion exposure is too much motion exposure" from a biomechanical standpoint. These issues were the focus of several industrial studies performed over a 6-yr period in 68 different industrial environments. Trunk motion and workplace conditions were assessed in workers exposed to high risk of LBD jobs and compared to trunk motions and work place conditions of low-risk jobs (Marras et al., 1993, 1995). A trunk goniometer (lumbar motion monitor or LMM) that has been used to document the trunk motion patterns of workers at the workplace is shown in Figure 11.33. Trunk motion and workplace conditions associated with the high-risk and low-risk environments are listed in Table 11.6. Based upon these findings, a five factor multiple logistic regression model was developed that is capable of discriminating between task exposure that indicate probability of high-risk group membership. These factors include: (1) frequency of lifting, (2) load moment (load weight multiplied by the distance of the load from the spine), (3) average twisting velocity (measured by the LMM), (4) maximum sagittal flexion angle through the job cycle (measured by the LMM), and (5) maximum lateral velocity (measured by the LMM). This LMM risk assessment model is the only model capable of assessing the *risk* of 3D trunk motion on the job. This model

FIGURE 11.33 The lumbar motion monitor (LMM).

has been shown to have a high degree of predictability (odds ratio = 10.7) compared to previous attempts to assess work-related LBD risk. The advantage of this assessment is that the evaluation provides information about risk that would take years to derive from historical accounts of incidence rates. The model has also been validated in a prospective study (Marras et al., 2000a, b). Chapter 49 further explains the logic and validity of this tool.

11.4.7 TLVs

Threshold Limit Values or TLVs have been recently introduced for controlling biomechanical risk to the back in the workplace. These limits have been introduced through the American Conference of Governmental Industrial Hygienists (ACGIH) and provide lifting weight limits as a function of lift origin "zones" and repetitions associated with occupational tasks. The lift origin zones are defined by the lift height off the ground and lift distance from the spine associated with the lift origin. Twelve zones are defined that related to lifts within $\pm 30^{\circ}$ of asymmetry from the sagittal plane. These zones are represented in three figures with each figure corresponding to different lift frequency and time exposures. Within each zone limits are specified based upon the best information available from several sources, which include: (1) EMG-assisted biomechanical models, (2) the 1993 revised lifting equation, and (3) the historical risk data associated with the LMM database. This tool is further described in Chapter 50.

TABLE 11.6 Descriptive Statistics of the Workplace and Trunk Motion Factors in Each of the Risk Groups

Factors	High Risk ($N = 111$)				Low Risk ($N = 124$)				Statistics t
	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum	
WORKPLACE FACTORS									
Lift rate (lifts/h)	175.89	8.65	15.30	900.00	118.83	169.09	5.40	1500.00	2.1[a]
Vertical load location at origin (m)	1.00	0.21	0.38	1.80	1.05	0.27	0.18	2.18	1.4
Vertical load location at destination (m)	1.04	0.22	0.55	1.79	1.15	0.26	0.25	1.88	3.2[b]
Vertical distance traveled by load (m)	0.23	0.17	0.00	0.76	0.25	0.22	0.00	1.04	0.8
Average weight handled (N)	84.74	79.39	0.45	423.61	29.30	48.87	0.45	280.92	6.4[b]
Maximum weight handled (N)	104.36	88.81	0.45	423.61	37.15	60.83	0.45	325.51	6.7[b]
Average horizontal distance between load and L_5-S_1 (N)	0.66	0.12	0.30	0.99	0.61	0.14	0.33	1.12	2.5[a]
Maximum horizontal distance between load and L_5-S_1 (N)	0.76	0.17	0.38	1.24	0.67	0.19	0.33	1.17	3.7[b]
Average moment (Nm)	55.26	51.41	0.16	258.23	17.70	29.18	0.17	150.72	6.8[b]
Maximum moment (Nm)	73.65	60.65	0.19	275.90	23.64	38.62	0.17	198.21	7.4[b]
Job satisfaction	5.96	2.26	1.00	10.00	7.28	1.95	1.00	10.00	4.7[b]
TRUNK MOTION FACTORS									
Sagittal Plane									
Maximum extension position (°)	−8.30	9.10	−30.82	18.96	−10.19	10.58	−30.00	33.12	3.5[b]
Maximum flexion position (°)	17.85	16.63	−13.96	45.00	10.37	16.02	−25.23	45.00	1.5
Range of motion (°)	31.50	15.67	7.50	75.00	23.82	14.22	399.00	67.74	3.8[b]
Average velocity (°/sec)	11.74	8.14	3.27	48.88	6.55	4.28	1.40	35.73	6.0[b]
Maximum velocity (°/sec)	55.00	38.23	14.20	207.55	38.69	26.52	9.02	193.29	3.7[b]
Maximum acceleration (°/sec^2)	316.73	224.57	80.61	1341.92	226.04	173.88	59.10	1120.10	4.2[b]
Maximum deceleration (°/sec^2)	−92.45	63.55	−514.08	−18.45	−83.32	47.71	−227.12	−4.57	1.2
Lateral Plane									
Maximum left bend (°)	−1.47	6.02	−16.80	24.49	−2.54	5.46	−23.80	13.96	1.4
Maximum right bend (°)	15.60	7.61	3.65	43.11	13.24	6.32	0.34	34.14	2.6[a]
Range of motion (°)	24.44	9.77	7.10	47.54	21.59	10.34	5.42	62.41	2.2[a]
Average velocity (°/sec)	10.28	4.54	3.12	33.11	7.15	3.16	2.13	18.86	6.1[b]
Maximum velocity (t/sec)	46.36	19.12	13.51	119.94	35.45	12.88	11.97	76.25	4.9[b]
Maximum acceleration (°/sec^2)	301.41	166.69	82.64	1030.29	229.29	90.90	66.72	495.88	4.1[b]
Maximum deceleration (°/sec^2)	−103.65	60.31	−376.75	0.00	−106.20	58.27	−294.83	0.00	0.3

(*Table continued*)

TABLE 11.6 *Continued*

	High Risk ($N = 111$)				Low Risk ($N = 124$)				
Factors	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum	Statistics t
Twisting Plane									
Maximum left twist (°)	1.21	9.08	−27.56	29.54	−1.92	5.36	−30.00	11.44	3.2[b]
Maximum right twist (°)	13.95	8.69	−13.45	30.00	10.83	6.08	−11.20	30.00	2.2[a]
Range of motion (°)	20.71	10.61	3.28	53.30	17.08	8.13	1.74	38.59	2.9[b]
Average velocity (°/sec)	8.71	6.61	1.02	34.77	5.44	3.19	0.66	17.44	3.8[b]
Maximum velocity (°/sec)	46.36	25.61	8.06	136.72	38.04	17.51	5.93	91.97	4.7[a]
Maximum acceleration (°/sec^2)	304.55	175.31	54.48	853.93	269.49	146.65	44.17	940.27	2.9[b]
Maximum deceleration (°/sec^2)	−88.52	70.30	−428.94	−5.84	−100.32	72.40	−325.93	−2.74	1.6[a]

[a]Significant at $\alpha \leq 0.05$ (two-sided).
[b]Significant at $\alpha \leq 0.01$ (two-sided).
Source: Adapted from Marras et al., *Spine* 18, pp. 617–628, 1993. With permission.

11.5 Summary

This chapter has shown that biomechanics provides one of the few means to *quantitatively* consider the implications of workplace design. Biomechanical design is important when a particular job is suspected of imposing large or repetitive forces on a particular structure of the body. It is particularly important to recognize that the internal structures of the body such as muscles are the primary loaders of the joint and tendon structures. In order to evaluate the risk of injury from a particular task, one must consider the contribution of both the external loads and internal loads upon the structure. Several quantitative models and assessment methods have been developed that systematically consider the internal loading imposed on the worker due to workplace layout and task requirements. Proper use of these models and methods involves recognizing the limitations and assumptions of each technique so that they are not applied inappropriately. When properly used, these assessments can help assess the risk of work-related injury and illness.

References

Adams, M.A., Freeman, B.J., Morrison, H.P., Nelson, I.W., and Dolan, P. Mechanical initiation of intervertebral disc degeneration, *Spine.*, 25, pp. 1625–1636, 2000.

Anderson, C.K., Chaffin, D.B., Herrin, G.D., and Matthews, L.S. A biomechanical model of the lumbosacral joint during lifting activities, *J. Biomech.*, 18, pp. 571–584, 1985.

Andersson, B.J., Ortengren, R., Nachemson, A.L., Elfstrom, G., and Broman, H. The sitting posture: an electromyographic and discometric study, *Orthop. Clin. North Am.*, 6, pp. 105–120, 1975.

Andersson, G.B. The epidemiology of spinal disorders, in *The Adult Spine: Principles and Practice*, Frymoyer, J.W., Ed., Lippincott-Raven Publishers, Philadelphia, 1997, 93–141.

Basmajian, J.V. and De Luca, C.J. *Muscles Alive: Their Functions Revealed by Electromyography*, 5th ed., Williams and Wilkins, Baltimore, MD, 1985.

Brinkmann, P., Biggermann, M., and Hilweg, D. Fatigue fracture of human lumbar vertebrae, *Clin Biomech (Bristol, Avon).*, 3, pp. S1–S23, 1988.

Cavanaugh, J.M. Neural mechanisms of lumbar pain, *Spine*, 20, pp. 1804–1809, 1995.

Cavanaugh, J.M., Ozaktay, A.C., Yamashita, T., Avramov, A., Getchell, T.V., and King, A.I. Mechanisms of low back pain: a neurophysiologic and neuroanatomic study, *Clin. Orthop.*, pp. 166–180, 1997.

Chaffin, D.B. A computerized biomechanical model: development of and use in studying gross body actions, *J. Biomech.*, 2, pp. 429–441, 1969.

Chaffin, D.B., Localized muscle fatigue — definiton and measurement, *J. Occup. Med.*, 15, pp. 346–354, 1973.

Chaffin, D.B. and Muzaffer, E. Three-dimensional biomechanical static strength predcition model sensitivity to postural and anthropometric innaccuracies, *IIE Transac.*, 23, pp. 215–227, 1991.

Chaffin, D.B., Andersson, G.B.J., and Martin, B.J. Occupational Biomechanics, New York, 1999.

Cholewicki, J. and S. McGill. Mechanical stability of the in vivo lumbar spine: Implications ofr injury and chronic low back pain, *Clin. Biomech. (Bristol, Avon)*, 11, pp. 1–15, 1996.

Cholewicki, J. and I.J. VanVliet. Relative contribution of trunk muscles to the stability of the lumbar spine during isometric exertions, *Clin. Biomech. (Bristol, Avon)*, 17, pp. 99–105, 2002.

Cholewicki, J., Polzhofer, G.K., and Radebold, A. Postural control of trunk during unstable sitting, *J Biomech.*, 33, pp. 1733–1737, 2000a.

Cholewicki, J., Simons, A.P., and Radebold, A. Effects of external trunk loads on lumbar spine stability, *J Biomech* 33, pp. 1377–1385, 2000b.

Gedalia, U., Solomonow, M., Zhou, B.H., Baratta, R.V., Lu, Y., and Harris, M. Biomechanics of increased exposure to lumbar injury caused by cyclic loading. Part 2. Recovery of reflexive muscular stability with rest, *Spine*, 24, pp. 2461–2467, 1999.

Granata, K.P. and Marras, W.S. An EMG-assisted model of loads on the lumbar spine during asymmetric trunk extensions, *J. Biomech.*, 26, pp. 1429–1438, 1993.

Granata, K.P. and Marras, W.S. The influence of trunk muscle coactivity on dynamic spinal loads, *Spine*, 20, pp. 913–919, 1995a.

Granata, K.P. and Marras, W.S. An EMG-assisted model of trunk loading during free-dynamic lifting, *J. Biomech.*, 28, pp. 1309–1317, 1995b.

Granata, K.P. and Marras, W.S. Cost-benefit of muscle cocontraction in protecting against spinal instability [In Process Citation], *Spine*, 25, pp. 1398–1404, 2000.

Granata, K.P. and Orishimo, K.F. Response of trunk muscle coactivation to changes in spinal stability, *J. Biomech.*, 34, pp. 1117–1123, 2001.

Granata, K.P. and Wilson, S.E. Trunk posture and spinal stability, *Clin. Biomech. (Bristol, Avon)*, 16, pp. 650–659, 2001.

Granata, K.P., Marras, W.S. and Davis, K.G. Biomechanical assessment of lifting dynamics, muscle activity and spinal loads while using three different styles of lifting belt, *Clin. Biomech. (Bristol, Avon)*, 12, pp. 107–115, 1997.

Granata, K.P., Orishimo, K.F., and Sanford, A.H. Trunk muscle coactivation in preparation for sudden load, *J. Electromyogr. Kinesiol.*, 11, pp. 247–254, 2001.

Grandjean, E. *Fitting the Task to the Man: An Ergonomic Approach*, Taylor & Francis, Ltd., London, 1982.

Guo, H.R. Back Pain and U.S. Workers, American Occupational Health Conference, 1993.

Guo, H.R., Tanaka, S., Halperin, W.E., and Cameron, L.L. Back pain prevalence in US industry and estimates of lost workdays, *Am. J. Public Health.*, 89, pp. 1029–1035, 1999.

Hollbrook, T.L., Grazier, K., Kelsey, J.L., and Stauffer, R.N. The Frequency of Occurrence, Impact and Cost of Selected Musculoskeletal Conditions in the United States, American Academy of Orthopaedic Surgeons, Chicago, IL, 1984.

Hoy, M.G., Zajac, F.E., and Gordon, M.E. A musculoskeletal model of the human lower extremity: the effect of muscle, tendon, and moment arm on the moment-angle relationship of musculotendon actuators at the hip, knee, and ankle, *J. Biomech.*, 23, pp. 157–169, 1990.

Jager, M., Luttmann, A. and Laurig, W. Lumbar load during one-hand bricklaying, *Int. J. Indust. Ergo.*, 8, pp. 261–277, 1991.

Khalsa, P.S. Biomechanics of musculoskeletal pain: dynamics of the neuromatrix, *J. Electromyogr. Kinesiol.*, 14, pp. 109–120, 2004.

Kim, J., Stuart-Buttle C., and Marras, W.S. The Effects of Mats on Back and Leg Fatigue, *Applied Ergonomics* 25, pp. 29–34, 1994.

Konz, S.A. *Work Design: Industrial Ergonomics*, 2nd ed., Grid Publishing, Inc., Columbus, OH, 1983. With permission.)

Kovacs, K., Splittstoesser, R., Maronitis, A., and Marras, W.S. Grip force and muscle activity differences due to glove type, *AIHA J (Fairfax, Va)* 63, pp. 269–274, 2002.

Kroemer, K.H.E. Biomechanics of the Human Body, *In* G. Salvendy ed., Handbook of Human Factors. John Wiley and Sons, Inc., New York, 1987.

Lantz, S.A. and Schultz, A.B. Lumbar spine orthosis wearing. I. Restriction of gross body motions. *Spine* 11, pp. 834–837, 1986.

Lavender, S.A., Thomas, J.S., Chang, D., and Andersson, G.B. Effect of lifting belts, foot movement, and lift asymmetry on trunk motions, *Hum Factors*, 37, pp. 844–853, 1995.

Luo, X., Pietrobon, R., X.S. S, Liu, G.G. and Hey, L. Estimates and patterns of direct health care expenditures among individuals with back pain in the United States, *Spine*, 29, pp. 79–86, 2004.

Marras, W.S. and Granata, K.P. A biomechanical assessment and model of axial twisting in the thoracolumbar spine, *Spine*, 20, pp. 1440–1451, 1995.

Marras, W.S. Spine loading during trunk lateral bending motions, *J. Biomech.*, 30, pp. 697–703, 1997a.

Marras, W.S. The Development of an EMG-Assisted Model to Assess Spine Loading during Whole-Body Free-Dynamic Lifting, *J. Electromyogr. Kinesiol.*, 7, pp. 259–268, 1997b.

Marras, W.S. and Mirka, G.A. Electromyographic studies of the lumbar trunk musculature during the generation of low-level trunk acceleration, *J. Orthop. Res.*, 11, pp. 811–817, 1993.

Marras, W.S. and Reilly, C.H. Networks of internal trunk-loading activities under controlled trunk-motion conditions, *Spine*, 13, pp. 661–667, 1988.

Marras, W.S. and Schoenmarklin, R.W. Wrist motions in industry, *Ergonomics*, 36, pp. 341–351, 1993.

Marras, W.S. and Sommerich, C.M. A three-dimensional motion model of loads on the lumbar spine: I. Model structure, *Hum Factors*, 33, pp. 123–137, 1991a.

Marras, W.S. A three-dimensional motion model of loads on the lumbar spine: II. Model validation, *Hum Factors*, 33, pp. 139–149, 1991b.

Marras, W.S., Davis, K.G., and Splittstoesser, R.E. Spine loading during whole body free dynamic lifting, The Ohio State University, Columbus, OH, Grant #:R01 OH03289, 2001.

Marras, W.S., Fine, L.J., Ferguson, S.A. and Waters, T.R. The effectiveness of commonly used lifting assessment methods to identify industrial jobs associated with elevated risk of low-back disorders, *Ergonomics*, 42, pp. 229–245, 1999.

Marras, W.S., Jorgensen, M.J. and Davis, K.G. Effect of foot movement and an elastic lumbar back support on spinal loading during free-dynamic symmetric and asymmetric lifting exertions, *Ergonomics*, 43, pp. 653–668, 2000a.

Marras, W.S., Allread, W.G., Burr, D.L., and Fathallah, F.A. Prospective validation of a low-back disorder risk model and assessment of ergonomic interventions associated with manual materials handling tasks [In Process Citation]. *Ergonomics*, 43, pp. 1866–1886, 2000b.

Marras, W.S., Lavender, S.A., Leurgans, S.E., Fathallah, F.A., Ferguson, S.A., Allread, W.G., and Rajulu, S.L. Biomechanical risk factors for occupationally related low back disorders, *Ergonomics*, 38, pp. 377–410, 1995.

Marras, W.S., Lavender, S.A., Leurgans, S.E., Rajulu, S.L., Allread, W.G., Fathallah, F.A., and Ferguson, S.A. The role of dynamic three-dimensional trunk motion in occupationally-related low back disorders. The effects of workplace factors, trunk position, and trunk motion characteristics on risk of injury, *Spine*, 18, pp. 617–628, 1993.

McCoy, M., Congleton, J., Johnson, W. and Jaing, B. The role of lifting belts in manual lifting, *Int. J. Indus. Ergon.*, 2, pp. 256–259, 1988.

McGill, S. Low back disorder, *Human Kinetics*, 2002a.

McGill, S. Low back disorders: evidence-based prevention and rehabilitation, *Human Kinetics, Champaign, IL*, 2002b.

McGill, S., Seguin, J., and Bennett, G. Passive stiffness of the lumbar torso in flexion, extension, lateral bending, and axial rotation. Effect of belt wearing and breath holding, *Spine*, 19, pp. 696–704, 1994.

McGill, S.M. Abdominal belts in industry: a position paper on their assets, liabilities and use, *Am. Ind. Hyg. Assoc. J.*, 54, pp. 752–754, 1993.

McGill, S.M. The biomechanics of low back injury: implications on current practice in industry and the clinic, *J. Biomech.*, 30, pp. 465–475, 1997.

McGill, S.M. and Norman, R.W. Dynamically and statically determined low back moments during lifting, *J. Biomech.*, 18, pp. 877–885, 1985.

McGill, S.M. and Norman, R.W. Partitioning of the L4-L5 dynamic moment into disc, ligamentous, and muscular components during lifting [see comments], *Spine*, 11, pp. 666–678, 1986.

McGill, S.M., Hughson, R.L. and Parks, K. Changes in lumbar lordosis modify the role of the extensor muscles [In Process Citation], *Clin. Biomech. (Bristol, Avon)*, 15, pp. 777–780, 2000.

Mitchell, L.V., Lawler, F.H., Bowen, D., Mote, W., Asundi, P., and Purswell, J. Effectiveness and cost-effectiveness of employer-issued back belts in areas of high risk for back injury, *J. Occup. Med.*, 36, pp. 90–94, 1994.

Nachemson, A. Towards a better understanding of low-back pain: a review of the mechanics of the lumbar disc, *Rheumatol Rehabil*, 14, pp. 129–143, 1975.

NIOSH 1981. Work Practices Guide for Manual Lifting, Department of Health and Human Services (DHHS) NIOSH, Cincinnati, OH, 81–122.

NIOSH Workplace use of back belts, Cincinnati, OH, Publication No. 94–122, 1994.

Nordin, M., and Frankel, V. Basic Biomechanics of the Musculoskeletal System. Lea and Febiger, Philadelphia, PA, 1989.

NRC Work-related musculokeletal disorders: report, workshop summary, and workshop papers. National Academy Press, Washington D. C, 1999.

NRC Musculoskeletal disorders and the workplace: low back and upper extremity. National Academy Press, Washington D. C, 2001.

Panjabi, M.M. The stabilizing system of the spine. Part II. Neutral zone and instability hypothesis, *J. Spinal. Disord.*, 5, pp. 390–396; discussion 397, 1992a.

Panjabi, M.M. The stabilizing system of the spine. Part I. Function, dysfunction, adaptation, and enhancement, *J. Spinal. Disord.*, 5, pp. 383–389; discussion 397, 1992b.

Park, K. and Chaffin, D. A biomechanical evaluation of two methods of manual load lifting, *AIIE Trans.* 6, pp. 105–113, 1974.

Pope, M.H. Muybridge Lecture, International Society of Biomechanics XIVth Congress, Paris, France, 1993.

Praemer, A., Furner, S. and Rice, D.P. Musculoskeletal Conditions in the United States, pp. 23–33. American Academy of Orthopaedic Surgeons, Park Ridge, IL, 1992.

Rafacz, W. and McGill, S.M. Wearing an abdominal belt increases diastolic blood pressure, *J. Occup. Environ. Med.*, 38, pp. 925–927, 1996.

Reddell, C., Congleton, J., Hutchingson, R. and Montgomery, J. An evaluation of weight-lifting belt and back injury prevention training class for airline baggage handlers, *Appl. Ergon.*, 22, pp. 319–329, 1992.

Reilly, C.H. and Marras, W.S. Simulift: a simulation model of human trunk motion, *Spine*, 14, pp. 5–11, 1989.

Sanders, M.S. and McCormick, E.F. *Human Factors in Engineering and Design*, McGraw-Hill Inc., New York, 1993.

Schoenmarklin, R.W., Marras, W.S., and Leurgans, S.E. Industrial wrist motions and incidence of hand/wrist cumulative trauma disorders, *Ergonomics*, 37, pp. 1449–1459, 1994.

Schultz, A.B. and Andersson, G.B. Analysis of loads on the lumbar spine, *Spine*, 6, pp. 76–82, 1981.

Silverstein, M.A., Silverstein, B.A., and Franklin, G.M. Evidence for work-related musculoskeletal disorders: a scientific counterargument, *J. Occup. Environ. Med.*, 38, pp. 477–484, 1996.

Silverstein, B.A., Stetson, D.S., Keyserling, W.M., and Fine, L.J. Work-related musculoskeletal disorders: comparison of data sources for surveillance, *Am. J. Ind. Med.*, 31, pp. 600–608, 1997.

Solomonow, M. Ligaments: a source of work-related musculoskeletal disorders, *J. Electromyogr. Kinesiol.*, 14, pp. 49–60, 2004.

Solomonow, M., Zhou, B.H., Harris, M., Lu, Y. and Baratta, R.V. The ligamento-muscular stabilizing system of the spine, *Spine*, 23, pp. 2552–2562, 1998.

Solomonow, M., Zhou, B.H., Baratta, R.V., Lu, Y. and Harris, M. Biomechanics of increased exposure to lumbar injury caused by cyclic loading: Part 1. Loss of reflexive muscular stabilization, *Spine*, 24, pp. 2426–2434, 1999.

Solomonow, M., Zhou, B., Baratta, R.V., Zhu, M. and Lu, Y. Neuromuscular disorders associated with static lumbar flexion: a feline model, *J. Electromyogr. Kinesiol.*, 12, pp. 81–90, 2002.

Solomonow, M., He Zhou, B., Baratta, R.V., Lu, Y., Zhu, M. and Harris, M. Biexponential recovery model of lumbar viscoelastic laxity and reflexive muscular activity after prolonged cyclic loading, *Clin. Biomech., (Bristol, Avon)* 15, pp. 167–175, 2000.

Stubbs, M., Harris, M., Solomonow, M., Zhou, B., Lu, Y., and Baratta, R.V. Ligamento-muscular protective reflex in the lumbar spine of the feline, *J. Electromyogr. Kinesiol.*, 8, pp. 197–204, 1998.

Thelen, D.G., Schultz, A.B. and Ashton-Miller J.A. Co-contraction of lumbar muscles during the development of time-varying triaxial moments, *J. Orthop. Res.*, 13, pp. 390–398, 1995.

Tichauer, E.R. The Biomechanical Basis of Ergonomics: Anatomy applied to the design of work situations, John Wiley & Sons, New York, 1978.

Van Dieen, J.H., Hoozemans, M.J., and Toussaint, H.M. Stoop or squat: a review of biomechanical studies on lifting technique, *Clin. Biomech., (Bristol, Avon)* 14, pp. 685–696, 1999.

Videman, T., Nurminen, M., and Troup, J.D. 1990 Volvo Award in clinical sciences. Lumbar spinal pathology in cadaveric material in relation to history of back pain, occupation, and physical loading, *Spine*, 15, pp. 728–740, 1990.

Walsh, N.E. and Schwartz, R.K. The influence of prophylactic orthoses on abdominal strength and low back injury in the workplace [see comments], *Am. J. Phys. Med. Rehabil.*, 69, pp. 245–250, 1990.

Wang, J.L., Parnianpour, M., Shirazi-Adl, A., and Engin, A.E. Viscoelastic finite-element analysis of a lumbar motion segment in combined compression and sagittal flexion. Effect of loading rate, *Spine*, 25, pp. 310–318, 2000.

Wassell, J.T., Gardner, L.I., Landsittel, D.P., Johnston, J.J., and Johnston, J.M. A Prospective Study of Back Belts for Prevention of Back Pain and Injury, *J. Am. Me. Assoc.*, 284, pp. 2727–2732, 2000.

Waters, T.R., Putz-Anderson, V., Garg, A., and Fine, L.J. Revised NIOSH equation for the design and evaluation of manual lifting tasks, *Ergonomics*, 36, pp. 749–776, 1993.

27

Medical Management of Work-Related Musculoskeletal Disorders

Thomas Hales
National Institute for Occupational Safety and Health (NIOSH)

Patricia Bertsche
The Ohio State University

27.1 Introduction

The Bureau of Labor Statistics (BLS) reports that in 1994 nearly two thirds of the workplace illnesses were disorders associated with repeated trauma (one category of musculoskeletal disorders) (BLS, 1995). These figures do not include low back disorders associated with overexertion, which accounted for 380,000 lost time cases in 1993. The number of repeated trauma cases reported in 1994 was 332,000, a 10% increase from the 1993 figure. In fact, since 1982, the number of reported disorders associated with repeated trauma has been increasing each year (BLS, 1995). Not surprisingly, many health care providers (HCPs) find evaluating and treating these employees consumes an increasing proportion of their time and energy.

To prevent or reduce symptoms, signs, impairment, or disability associated with work-related musculoskeletal disorders (WRMSDs), employers, in collaboration with HCPs, should develop a medical management program which is outlined in Figure 27.1. This chapter provides assistance to employers setting up a medical management program and to HCPs managing these cases in two ways—first, by outlining the general principles and listing the components of a program needed to adequately evaluate

0-8493-1800-9/03/$0.00+$1.50

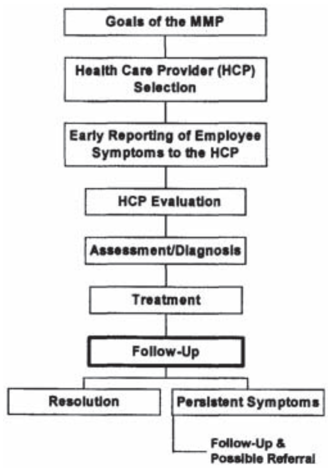

FIGURE 27.1 Overview of a medical management program (MMP).

and treat affected employees; second, by providing HCPs with practical guidance and forms to collect the appropriate information. These forms can then be incorporated into the employee's medical record.

27.2 Terminology

Before addressing the various components of a medical management program, the term musculoskeletal disorder must be defined. MSDs are disorders of the muscles, tendons, peripheral nerves, or vascular system not directly resulting from an acute or instantaneous event (e.g., slips or falls). These disorders are considered to be work-related when the work environment and the performance of work contribute significantly, but as one of a number of factors, to the causation of a multifactorial disease (WHO, 1985). Physical risk factors that cause or aggravate MSDs and that may be present at the workplace include, but are not limited to: repetitive, forceful, or prolonged exertions; frequent or heavy lifting; pushing, pulling, or carrying of heavy objects; fixed or awkward work postures; contact stress; localized or whole-body vibration; cold temperatures; and poor lighting leading to awkward postures. These workplace risk factors can be intensified by work organization characteristics, such as inadequate work-rest cycles, excessive work pace and/or duration, unaccustomed work, lack of task variability, machine-paced work, and piece rate.

27.3 Selection of a Health Care Provider (HCP)

An HCP is a practitioner operating within the scope of his or her license, registration, certification, or legally authorized practice. The evaluation and treatment of employees with WRMSDs should be performed by an HCP with experience and/or training in managing these disorders. Many HCPs are capable of providing these services, including physicians, occupational health nurses, physical therapists, occupational therapists, and hand therapists. Employers and employees may be more familiar with the services of physicians, therefore Table 27.1 provides information regarding some of the other HCPs who might be directly providing the care or coordinating the care of employees with WRMSDs. Considerations for the employer to use in selecting an HCP include:

- Specialized training and experience in ergonomics and the treatment of work-related musculoskeletal disorders
- Current working knowledge of the worksite and the specific industry
- Willingness to periodically tour the worksite

TABLE 27.1 Non-Physician Health Care Providers Who Might Be Involved in the Medical Management of Work-Related Musculoskeletal Disorders (Not intended to be all-inclusive)

Profession	Scope of Practice	Training/Experience	Services They Provide
Occupational Health Nurse (OHN)	An OHN is a Registered Nurse (RN), independent licensure with scope defined by individual state boards of nursing; certification is voluntary (COHN); Advanced practice nurses (nurse practitioners) treat independently or provide medical treatment with protocol depending on requirements of state licensing board. RNs refer to physicians and other health care providers when treatment beyond their scope of practice is required.	Basic education includes complete assessment (history and physical examination) of all body systems; OHNs have academic and/or continuing education in assessment of the musculoskeletal and nervous systems and diagnosis, treatment, and rehabilitation of work-related musculoskeletal disorders.	Assessment, treatment of common work-related musculoskeletal disorders, particularly in early stages (under protocol when required by state statute), referral to other appropriate health care providers as needed, and rehabilitation including case management; Preventive services include trend analysis, education and training, and involvement in the job improvement process including job analysis.
Occupational Therapist (OT)	49 states, the District of Columbia, Guam, and Puerto Rico have laws regulating the profession; The American Occupational Therapy Certification Board's national certification exam is a basic requirement in the states/jurisdictions that license or certify OTs. Generally, an OT may independently provide services, however, in certain states, occupational therapy laws/regulations require physician referral for services for specific medical conditions.	OTs have either a bachelor's or master's degree and pursue continuing education and extensive on-the-job training to specialize in work-related musculoskeletal disabilities; OTs have a comprehensive background in the biological and behavioral sciences; knowledge and application of the components of human performance including psychosocial, neurological, cognitive, perceptual, and motor function.	OTs use standardized tests, observational skills, activities and tasks designed to evaluate specific work-related skills, functional abilities, physical abilities, and behaviors. Examples of assessments include: functional capacity evaluation, physical capacity testing, examination of essential functions of a job. Other services include work hardening and involvement in the job improvement process such as job analysis and workstation and tool modification.
Physical Therapist (PT)	PTs licensed in all states, the District of Columbia, Puerto Rico, and the U.S. Virgin Islands; Direct physician oversight is not required. Of the 53 jurisdictions, 44 permit physical therapy evaluation without physician referral.	PTs have either a bachelor's or graduate degree and pursue continuing education to specialize in prevention and rehabilitation of work-related musculoskeletal disorders. PTs' basic education includes courses in anthropometrics, biomechanics, ergonomic interventions, kinesiology, movement and posture analysis, the components of human psychophysical performance, orthotic prescription, fabrication, and application of supportive devices.	PTs evaluate a variety of conditions such as abnormalities of body alignment and movement patterns; impaired motor function and learning; impaired sensation; limitations of joint motion; muscle weakness; and pain. PTs perform tests and measures such as batteries of work performance; assessment of work hardening or conditioning; determination of dynamic capabilities and limitations during specific work activities. Involvement in the job improvement process including analysis of jobs or activities, and workstation or tool modifications.
Hand Therapist (HT)	A Hand Therapist is either an OT or PT who voluntarily becomes certified by the Hand Therapy Certification Commission. Certified HTs specialize in upper extremity rehabilitation.	HTs have specialized training and experience in assessment and rehabilitation of work-related musculoskeletal disorders.	Services include diagnostic work up of quantitative sensory testing to determine peripheral neuropathy, grip strength, and motor testing to determine the localization of muscular tenderness areas of inflammation; physical or functional capacity evaluations. HTs apply treatments such as thermotherapy, ultrasound, and electric stimulation; re-education home exercise programs, splintage, pain management, soft tissue mobilization and myofascial release. HTs are skilled in work task analysis and therefore are well suited for involvement in the job improvement process.

- Willingness to communicate with the employer and employees (Louis, 1987; Haig et al., 1990)
- Experience in the case management of work-related musculoskeletal disorders
- Willingness to consider conservative therapy prior to surgery
- History of successful treatment of work-related musculoskeletal disorders

27.4 Early Reporting of Symptoms and Access to Health Care Providers

The case management process begins with an employee informing his or her employer of the presence of musculoskeletal symptoms or signs. Generally, the earlier that symptoms are identified, an evaluation completed, and treatment initiated, the likelihood of a significant disorder developing is reduced. Early treatment of many MSDs has been shown to reduce their severity, duration of treatment, and ultimate disability (Haig et al., 1990; Wood, 1987; Wiesel et al., 1984; Mayer et al., 1987). There can be various workplace situations influencing an employee's decision to report symptoms. These situations can result in employees over-reporting, or under-reporting, symptoms. In either case, to prevent severe disorders from occurring, employees must not be subject to reprisals or discrimination based on reporting symptoms to their supervisors.

Supervisors and foremen are not trained to evaluate and assess MSDs. To prevent supervisors or other plant personnel from performing triage, employees reporting persistent musculoskeletal symptoms (e.g., symptoms lasting seven days from onset, or symptoms that interfere with the employee's ability to perform the job) should have the opportunity for a prompt HCP evaluation. If an HCP is available at the workplace, this initial assessment should be offered when the employee reports symptoms or at least within two days. If the HCP is offsite, the employer should make available an assessment to the employee promptly, but no later than a week after the signs or symptoms are reported. This is not meant to imply that employers should wait seven days from onset of all employee's symptoms before referring the employee to an HCP. There are foreseeable circumstances where immediate evaluation by an HCP would be warranted. For example, an employee who reports to the supervisor that he/she is experiencing severe low back pain with numbness and tingling radiating down his/her leg, an inability to sleep due to the pain, and obvious difficulty walking should immediately be referred to the HCP.

27.5 Health Care Providers Familiarity with Employee's Job

HCPs who evaluate employees, determine an employee's functional capabilities, and prepare opinions regarding work-relatedness and work-readiness, must be familiar with employee jobs and job tasks. Being familiar with employee jobs not only assists HCPs in making informed case management decisions, but also demonstrates to employers and employees the importance HCPs place on making informed decisions, assists with the identification of workplace hazards that cause or aggravate MSDs, assists with the identification of alternate duty jobs, and can help establish the proper diagnosis for the employee's condition.

Critical to this process is open lines of communication with the employer, employee, and the HCP. The employer should appoint a contact person who is familiar with plant jobs and workplace risk factors to communicate and coordinate with the HCP. In addition, HCPs should perform a plant walk-through. Once familiar with plant operations and job tasks, the HCP can periodically revisit the facility to remain knowledgeable about working conditions. Other approaches to become familiar with jobs and job tasks include review of job analysis reports, job surveys or risk factor checklists, detailed job descriptions, job safety analyses, photographs and/or videotapes accompanied by narrative or written descriptions, and interviewing the employee.

27.6 Evaluation of the Employee

The HCP evaluation of the symptomatic employee should contain a relevant occupational and health history, a physical examination, laboratory tests appropriate to the reported signs or symptoms, and conclude with an initial assessment/diagnosis. If the HCP providing the initial evaluation does not have the training or experience to make a preliminary assessment or diagnosis, the employee should be referred to an HCP with such training and experience. The content of the evaluation is outlined below with a recording form available (see Form 1).

1. Characterize the symptoms and history
   - Onset (date; circumstance; abrupt vs. gradual, etc.)
   - Duration and frequency
   - Quality (pain; tingling; numbness; swelling; tenderness, etc.)
   - Intensity (mild; moderate; severe; other rating scales)
   - Location
   - Radiation
   - Exacerbating and/or relieving factors or activities (both on-the-job and off-the-job)
   - Prior treatments
2. Relevant considerations:
   - Demographics (e.g., age; gender; hand dominance)
   - Past medical history (e.g., prior injuries or disorders related to the affected body part)
   - Recreational activities, hobbies, household activities
   - Occupational history with emphasis on the (a) job the employee was performing when the symptoms were first noticed, (b) prior job if the employee recently changed jobs, (c) amount of time spent on that job, and (d) whether the employee was working any other "moonlighting" or part-time jobs.
3. Characterize the job:

   Becoming familiar with an employee's job is a critical component of the HCP evaluation and treatment process. In addition to collecting the information from the plant contact person and plant walk-through (described above), employees should be interviewed regarding their work activities. The employee should be asked to describe their required job tasks with respect to known workplace risk factors for MSDs and the duration of exposure such as hours per day, days per week and shift work. Workplace risk factors for MSDs include repetitive, forceful, or prolonged exertions; frequent or heavy lifting or lifting in awkward postures (e.g., twisting, trunk flexion, or lateral bending); pushing, pulling, or carrying of heavy objects; fixed or awkward work postures; contact stress; localized or whole-body vibration; cold temperatures; and others. The employee should also be asked if there has been any recent changes in their job, such as longer hours, increased pace, new tasks or equipment, or new work methods which may have caused or contributed to the current illness.
4. Physical examination:

   The physical examination should be targeted to the presenting symptoms and history. Components of the exam include inspection (redness, swelling, deformities, atrophy, etc.), range of motion, palpation, sensory and motor function (including functional assessment), and appropriate maneuvers (e.g., Finkelstein's). It is important to note that clinical examinations may not identify the specific structure affected, nor find classic signs of inflammation (e.g., redness, warmth, swelling). This should not be surprising since the role of inflammation in the pathophysiology of these disorders is unclear (Nirschl, 1990). For further information on the content of an appropriate exam, or the technique to perform the exam, please consult the following references: AHCPR, 1994; ASSH, 1990; Hoppenfield, 1976; Tubiana et al., 1984.

5. Assessment and diagnosis:

   For each employee referred for an assessment, the HCP should make a specific diagnosis consistent with the current International Classification of Diseases, or the HCP should summarize the findings of his or her assessment. Terms such as repetitive motion disorders (RMDs), repetitive strain injury (RSI), overuse syndrome, cumulative trauma disorders (CTDs), and work-related musculoskeletal disorder (WRMSD) are not ICD diagnoses and, although useful as general terms, should not be used as medical diagnoses. Given the difficulty in establishing the specific structure affected, many diagnoses should describe the anatomic location of the symptoms without a specific structure diagnosis (e.g., unspecified neck symptoms or disorders should be listed as ICD-9 723.9; unspecified disorders of the soft tissues should be listed as ICD-9 729.9). When a specific anatomical structure can be ascertained, most of these conditions involve the muscles or tendons (unspecified disorders of muscle, ligament, and fascia should be listed at ICD-9 728.9; unspecified disorders of synovium, tendon, and bursa should be listed as ICD-8 727.9). Table 27.2 provides a listing of ICD-9 codes.

   The HCP should assist in determining whether occupational risk factors are suspected to have caused, contributed to, or exacerbated the condition. Factors helpful in making this determination are:

   - Is the medical condition known to be associated with work?
   - Does the job involve risk factors (based on job surveys or job analysis information) associated with the presenting symptoms?
   - Is the employee's degree of exposure consistent with those reported in the literature?
   - Are there other relevant considerations (e.g., unaccustomed work, overtime, etc.)?

27.7 Treatment of the Employee

Before initiating treatment, the HCP should document the specific treatment goals (e.g., symptom resolution or restoring of functional capacity), expected duration of treatment, dates for follow-up evaluations, and time frames for achieving the treatment goals. Resting the symptomatic area, and treatment of soft tissue and tendon disorders are the mainstays of conservative treatment. Despite the wide application of some therapeutic modalities, many are untested in controlled clinical trials.

Resting the Symptomatic Area

Reducing or eliminating employee exposure to musculoskeletal risk factors through engineering and administrative controls in the workplace is the most effective way to rest the symptomatic area while allowing employees to remain productive members of the workforce (Upfal, 1994). Until effective controls are installed, employee exposure to workplace risk factors can be reduced through restricted duty and/or temporary job transfer. The specific amount of work reduction for employees on restricted duty must be individualized; however, the following principles apply: the degree of restriction should be proportional to the condition severity and to the frequency and duration of exposure to relevant risk factors involved in the original job. HCPs are responsible for determining the physical capabilities and work restrictions of the affected worker. The employer is responsible for finding a job consistent with these temporary restrictions. The employer's contact person (who is knowledgeable about the employee's job requirements and their associated risk factors) is critically important to this process. The contact person should communicate and collaborate with the HCP so that appropriate job placement of the employee occurs during the recovery period. Written return-to-work plans ensure that the HCP, the employee, and the employer all understand the steps recommended to promote recovery, and ensure that the employer understands what his or her responsibility is for returning the employee to work. A form is included to collect and distribute this written plan (Form 2). The HCP is also responsible for employee follow-up to document a reduction in symptoms during the recovery period.

TABLE 27.2 Specific ICD-9 Diagnoses Referred to as Musculoskeletal Disorders by ICD-9 Numbers

Tendon, synovium, and bursa disorders	**727**
Trigger finger (acquired)	727.03
Radial styloid tenosynovitis (deQuervain's)	727.04
Other tenosynovitis of hand and wrist	727.05
Specific bursitides often of occupational origin	727.2
Unspecified disorder of synovium, tendon, and bursa	727.9
Peripheral enthesopathies	**726**
Rotator cuff syndrome, supraspinatus syndrome	726.10
Bicipital tenosynovitis	726.12
Medial epicondylitis	726.31
Lateral epicondylitis (tennis elbow)	726.32
Unspecified enthesopathy	726.9
Disorders of muscle, ligament, and fascia	**728**
Game-Keepers thumb	728.8
Muscle spasm	728.85
Unspecified disorder of muscle, ligament, and fascia	728.9
Other disorders of soft tissues	**729**
Myalgia, myositis, fibromyositis	729.1
Swelling of limb	729.81
Cramp	729.82
Unspecified disorders of soft tissue	729.9
Osteoarthritis	**715**
Mononeuritis of upper limb	**354**
Carpal tunnel syndrome (median nerve entrapment)	354.0
Cubital tunnel syndrome	354.2
Tardy ulnar nerve palsy	354.2
Lesions of the radial nerve	354.3
Unspecified mononeuritis of upper limb	354.9
Peripheral vascular disease	**443**
Raynaud's syndrome	443.0
Hand-Arm Vibration Syndrome	443.0
Vibration White Finger	443.0
Arterial embolism and thrombosis	**444**
Hypothenar hammer syndrome	444.2
Ulnar artery thrombosis	444.21
Nerve root and plexus disorders	**353**
Brachial plexus lesions	353.0
Cervical rib syndrome	353.0
Costoclavicular syndrome	353.0
Scalenus anticus syndrome	353.0
Thoracic outlet syndrome	353.0
Unspecified nerve root and plexus disorder	353.9
Spondylosis (inflammation of the vertebrae)	**721**
Cervical without myelopathy	721.0
Cervical with myelopathy	721.1
Thoracic without myelopathy	721.2
Lumbarsacral without myelopathy	721.3
Thoracic or lumbar with myelopathy	721.4
Intervertebral disc disorders	**722**
Displacement of cervical disc	722.0
Displacement of thoracic or lumbar disc	722.1
Degeneration of the cervical disc	722.4
Degeneration of the thoracic or lumbar disc	722.5
Intervertebral disc disorder with myelopathy	722.17
Disorders of the cervical region	**723**
Cervicalgia (pain in neck)	723.1
Cervicobrachial syndrome (diffuse)	723.3
Unspecified neck symptoms or disorders	723.9
Unspecified Disorders of the Back	**724**
Low back pain	724.2

FORM 1—Occupational and Health History Recording Form for Musculoskeletal Disorders

Name: ______________________ **Dept:** ______________________ **Job Title:** ______________________

Age: ____ **yrs** **Gender:** ____ **F** ___ **M** **Length of time at the plant:** _______ **mo/yrs**

Dominate Hand: ____ **R** ____ **L** ___ **Both** **Length of time on-the-job:** _______ **mo/yrs**

Symptom Characterization:

Onset: Date: ________________ Abrupt vs. Gradual: ______________

Quality: (let employee describe, check all that apply)

___ pain ___ tenderness ___ weakness ___ soreness ___ numbness

___ tingling ___ burning ___ swelling ___ cramping ___ throbbing

Duration: ________________ Frequency: ________________

Intensity: (mild, moderate, or severe) __________________

Location: (R = right, L = left) ___ neck ___ upper arm ___ lower arm ___ back ___ upper leg ___ foot

(Check all that apply) ___ shoulder ___ elbow ___ hand/wrist ___ hip ___ lower leg

Radiation: (R = right, L = left) ___ neck ___ upper arm ___ lower arm ___ back ___ upper leg ___ foot

(Check all that apply) ___ shoulder ___ elbow ___ hand/wrist ___ hip ___ lower leg

Exacerbating or relieving activities (both on-the-job and off-the-job):

Exacerbating: 1) _________________ 2) _________________ 3) _________________

Relieving: 1) _________________ 2) _________________ 3) _________________

Past Medical History (prior injuries or disorders):

1) ________________________________ 3) ________________________________

2) ________________________________ 4) ________________________________

Recreational Activities, Hobbies, Household Activities:

1) ________________________________ 3) ________________________________

2) ________________________________ 4) ________________________________

Occupational History:

1) ________________________________ 3) ________________________________

2) ________________________________ 4) ________________________________

Characterize the Job:

Forceful, repetitive or sustained **exertions** can be estimated from production standards, employee ratings of efforts required to complete job tasks, descriptions of work objects and tools, weights of work objects and tools, and length of the workday. Extreme, repetitive or sustained **postures** can be estimated from a description of work methods and equipment. Employees can demonstrate the posture required for each step of the job task, or simulate the workstation in the examining room. Insufficient rest, pauses, or **recovery time** and be estimated from a description of rest breaks, production standards, work flow, and work organization factors. Extreme levels, repeated or long exposure to **vibration** can be estimated from a description of hand tools, or equipment. **Cold temperatures**, repeated or long exposure to cold can be based on temperature measurements, estimated from a description of the work environment, and the duration of time spent in cold areas.

Physical Stress	Property		
	Magnitude	Repetition Rate	Duration
Force			
Joint Angle			
Recovery			
Vibration			
Temperature			

FORM 2—Musculoskeletal Disorder Management Plan

Forward Only Work Related Medical Information to the Employer

Date of Assessment: ________________

Name: ______________ Date of Birth: _____________

Employer: ___________ Contact Person: _________________ Phone: _________ FAX: ___________

Diagnosis/Assessment:____

____

Treatment Plan: (e.g., medications/dosage, splints, physical or occupational therapy including frequency and duration of treatment, etc.)

____

____

Next Appointment: _____________________

Other Scheduled Appointments:

____

WORK STATUS

Is the Employee able to perform his/her regular work?

____ Yes, Full duty

____ No, Remove from Work Environment until ______________

____ No, Modified or Alternate Work until ______________

(Complete Activity Checklist below for Job Modifications)

Name: ______________________________

Description of Restricted Work Activity

Activity	Duration	Frequency
a. Sitting	____ Hrs. Per Day	____ Hrs. at a Time
b. Standing	____ Hrs. Per Day	____ Hrs. at a Time
c. Walking	____ Hrs. Per Day	____ Hrs. at a Time
d. Lift/Carry:____ lbs.	____ Hrs. Per Day	____ Times Per Hr.
e. Climbing Stairs	____ Hrs. Per Day	____ Times Per Hr.
f. Climbing Ladders	____ Hrs. Per Day	____ Times Per Hr.
g. Kneeling	____ Hrs. Per Day	____ Times Per Hr.
h. Bending at Waist	____ Hrs. Per Day	____ Times Per Hr.
I. Squatting	____ Hrs. Per Day	____ Times Per Hr.
j. Twisting	____ Hrs. Per Day	____ Times Per Hr.
k. Pull/Push: ____ lbs.	____ Hrs. Per Day	____ Times Per Hr.
l. Reach Above Shoulder	____ Hrs. Per Day	____ Times Per Hr. ____ L ____ R
m. Extended Reaching	____ Hrs. Per Day	____ Times Per Hr. ____ L ____ R
n. Neck bend/twisting	____ Hrs. Per Day	____ Times Per Hr.
o. Elbow/Forearm Twist	____ Hrs. Per Day	____ Times Per Hr. ____ L ____ R
p. Hand/Wrist Bending	____ Hrs. Per Day	____ Times Per Hr. ____ L ____ R
q. Pinch Gripping	____ Hrs. Per Day	____ Times Per Hr. ____ L ____ R
r. Forceful Grasping	____ Hrs. Per Day	____ Times Per Hr. ____ L ____ R
s. Continuous Keyboard Use	____ Hrs. Per Day	____ Times Per Hr.
t. Vibrating Tool/Equip Use	____ Hrs. Per Day	____ Times Per Hr. ____ L ____ R
u. Ankle/Foot Bend/Twist	____ Hrs. Per Day	____ Times Per Hr. ____ L ____ R
v. Cold Temperature	____ Hrs. Per Day	

Other Restricted Job Tasks (including frequency and duration): ______________________________

____

Other Specific Job Recommendations: ____

____

Health Care Provider Name: ________________________

Address: _____________________________________ City/State/Zip: ______________________________

Phone: (___)___________ FAX: (___)____________

Copy of Form Given to Employee: ____ Yes ____ No

Health Care Provider Signature: ______________ Date: __________________

Complete removal from the work environment should be avoided unless the employer is unable to accommodate the prescribed work restrictions. Research has documented that the longer the employee is off work, the less likely he/she will return to work (Vallfors, 1985). In these cases, the employer's contact person and the employee should be in day-to-day contact, and the employee can be encouraged to participate in a fitness program that does not involve the injured anatomical area.

Wrist immobilization devices, such as wrist splints or supports, can help rest the symptomatic area in some cases. These devices are especially effective off the job, particularly during sleep. They should be dispensed to individuals with MSDs only by HCPs with the training and experience in the positive and potentially negative aspects of these devices. Wrist splints, typically worn by patients with possible carpal tunnel syndrome, should not be worn at work unless the HCP determines that the employee's job tasks do not require wrist deviation or bending. Struggling against a splint can exacerbate the medical condition due to the increased force needed to overcome the splint. Splinting may also cause other joint areas (elbows or shoulders) to become symptomatic as work technique is altered. Recommended periods of immobilization vary from several weeks to months depending on the nature and severity of the disorder. Immobilization should be prescribed judiciously and monitored carefully to prevent iatrogenic complications (e.g., disuse muscle atrophy).

The *prophylactic* use of immobilization devices worn on or attached to the wrist or back is not recommended. Research indicates wrist splints have not been found to prevent distal upper extremity musculoskeletal disorders (Rempel, 1994). Likewise, there is no rigorous scientific evidence that back belts or back supports *prevent* injury, and their use is not recommended for prevention of low back problems (NIOSH, 1994; Mitchell et al., 1994). Where the employee is allowed to use a device that is worn on or attached to the wrist or back, the employer, in conjunction with a HCP, should inform each employee of the risks and potential health effects associated with their use in the workplace, and train each employee in the appropriate use of these devices. (McGill, 1993)

The HCP should advise affected employees about the potential risk of continuing non-modified work, or spending significant amounts of time on hobbies, recreational activities, and other personal habits that may adversely affect their condition (e.g., requires the use of the injured body part). However, as mentioned above, the employee should engage in a fitness program designed for exercise and aerobic conditioning that does not involve the injured anatomical area.

Thermal (more frequently cold) Therapy

Such treatment is generally considered useful in the acute phase of some MSDs. Cold therapy may be contraindicated for other conditions (e.g., neurovascular).

Oral Medications

Aspirin or other nonsteroidal anti-inflammatory agents (NSAIA) are useful in reducing the severity of symptoms either through their analgesic or anti-inflammatory properties. Their gastrointestinal and renal side effects, however, make their prophylactic use among asymptomatic employees inappropriate, and may limit their usefulness among employees with chronic symptoms. In short, NSAIAs should not be used prophylactically.

It must be noted that the effectiveness of Vitamin B-6 for treatment of musculoskeletal disorders has not been established (Amadio, 1985; Stransky et al., 1989; Spooner et al., 1993). Additionally, at this time there is no scientifically valid research that establishes the effectiveness of Vitamin B-6 for *preventing* the occurrence of musculoskeletal disorders.

Stretching and Strengthening

A valuable adjunct in individual cases, this approach should be under the guidance of an appropriately trained HCP (e.g., physiatrists, physical and occupational therapists). Exercises that involve stressful motions or an extreme range of motions, or that reduce rest periods may be harmful.

Hot Wax

At this time there is no scientific evidence regarding the effectiveness of hot wax treatments as a preventative measure or as a therapeutic modality.

Steroid Injections

For some disorders resistant to conservative treatment, local injection of a corticosteroid by an experienced physician may be indicated. The addition of a local anesthetic agent to the injection can provide valuable diagnostic information.

Surgery

With an effective ergonomics and medical management program, surgery for work-related MSDs should be needed rarely. Surgical intervention should be used for objective medical conditions and should have proven effectiveness. While the indications for prompt or emergency surgical intervention may still be present (e.g., ulnar artery thrombosis), surgery should be reserved for severe cases (e.g., very high levels of pain resulting in significant functional limitations) not responding to an adequate trial of conservative therapy.

27.8 Follow-up and Return to Work

Follow-up

Many, if not most, WRMSDs improve with conservative measures. HCPs should follow up the symptomatic employee to document improvement, or to reevaluate employees who have not improved. The time frame for this follow-up depends on the symptom type, duration, and severity. A clinical exam or telephone contact with the employee should be made once a week, followed by a complete reevaluation within ten days from the last examination if the employee's symptoms are not improving. Where HCPs are available at the workplace, monitoring the symptomatic employee should occur every 3 to 5 working days depending on the clinical severity of the disorder (Wiesel et al., 1984; Wiesel et al., 1994).

In reassessing employees who have not improved, the following should be considered:

- Is the diagnosis correct?
- Are the treatment goals appropriate?
- Have the MSD risk factors on and off the job been addressed?
- Is referral appropriate?

If the job's relevant risk factors have been eliminated but the employee's symptoms persist, it is important for the HCP to realize that employee reactions to pain and functional limitations may prolong the recovery period. Strategies to help the employee cope with the pain and stress associated with these disorders should be incorporated into the employee's treatment plan. The time frames for considering referral depends on the primary HCP's training and expertise, in addition to the type, duration, and severity of the condition. In general, severe symptoms with objective physical examination findings interfering with an employee's ability to perform his/her job should be referred to an appropriate HCP specialist sooner than milder symptoms without objective findings.

Return to Work

If an employee's treatment plan required time away from work, the next step is to return the employee to work in a manner that will minimize the chance for re-injury. Employees returning to the same job without a modification of the work environment are at risk for a recurrence. Key to the return to work process is open communication among the employee, the HCPs, and management. This will allow: (1)

prompt treatment, (2) an expedient return to work consistent with the employee's health status and job requirements, and (3) regular follow-up to manage symptoms and modify work restrictions as appropriate. The principles guiding the return to work determination include the type of MSD condition, the severity of the MSD condition, and the MSD risk factors present on the job.

Employees with MSDs who have diffkiculty remaining at work or returning to work in the expected timeframes are candidates for rehabilitation therapy. Rehabilitation refers to the process in which an injured worker follows a specific program that promotes healing and helps him or her return to work. During the rehabilitation process, psychosocial factors (factors present both on the job, and off the job, that can compromise an individual's ability to cope with symptoms, physical disorders, and functional limitations) should be addressed.

27.9 Screening

Currently there is no scientific evidence that validates the use of preassignment medical examinations, job simulation tests, or other screening tests as a valid predictor of which employees are likely to develop MSDs (Frymoyer, 1992; Werner et al., 1994; Cohen et al., 1994). Literature findings are mixed on the use of preplacement strength testing as a valid predictor of back injury.

27.10 Conclusion

The financial and human costs of work-related musculoskeletal disorders to our society are staggering. This chapter on the medical management of these disorders should help employers and HCPs wishing to prevent or reduce the severity of these disorders, resulting in a healthier, more productive workplace.

Acknowledgments/Disclaimer

We would like to thank the individuals and professional associations who contributed to the draft ANSI Z-365 standard, and the draft OSHA Ergonomic Protection Standard. Ms. Bertsche's contribution to this chapter occurred while a visiting scientist at the National Institute for Occupational Safety and Health (NIOSH), from the U.S. Department of Labor Occupational Safety and Health Administration (OSHA). This chapter represents the views of the authors and does not constitute official policy of NIOSH.

References

AHCPR (1994). Acute Low Back Problems in Adults: Assessment and Treatment. U.S. Dept of Health and Human Services, Public Health Service, Agency for Health Care Policy and Research. Rockville, MD. Publication No. 95–0643.

Amadio PC (1985). Pyridoxine as an adjunct in the treatment of carpal tunnel syndrome. *J Hand Surg;* 10A:237–241.

ANSI (1995). ANSI Z-365 Control of Work-Related Cumulative Trauma Disorders Part 1: Upper Extremities. American National Standards Institute. Chicago, IL: Working draft 4/17/95.

ASSH (1990). *The Hand: Examination and Diagnosis,* 3rd ed. American Society for Surgery of the Hand. New York, NY; Churchill Livingstone.

BLS (1995). Workplace injuries and illnesses in 1994. U.S. Department of Labor, Bureau of Labor Statistics. Washington, D.C.

Bongers PM, De Winter CR, Kompier MA, Hildebranndt VH (1993). Psychosocial factors at work and musculoskeletal disease. *Scand J Work Environ Health;* 19:297–312.

Cohen JE, Goel V, Frank JW, Gibson ES (1994). Predicting risk of back injuries, absenteeism, and chronic disability. *J Occup Med;* 36(10):1093–1099.

Day DE (1987). Prevention and return to work aspects of cumulative trauma disorders in the workplace. *Seminars in Occup Med;* 2(l):57–63.

Frymoyer JW (1992). Can low back pain disability be prevented? *Bailliere's Clinical Rheumatology;* 6(3):595–607.

Haig A, Linton P, McIntosh M, Moneta L, Mead P (1990). Aggressive early medical management by a specialist in physical medicine and rehabilitation: effect on lost time due to injuries in hospital employees. *J Occup Med;* 32(3):241–244.

Hoppenfield S (1976). *Physical Examination of the Spine and Extremities*. Norwalk, CT: Appleton Century Crofts.

Kiefhaber TR, Stern PH (1992). Upper extremity tendinitis and overuse syndromes in the athlete. *Clinics in Sports Med;* 11(1):39–55.

Louis DS (1987). Cumulative trauma disorders. *J Hand Surg;* 12A(5):823–825.

Mayer TG, Gatchel RJ, Hayer H et al. (1987). A prospective two-year study of functional restoration in industrial low back injury: an objective assessment procedure. *JAMA;* 258:1763–1767.

McGill SM (1993). Abdominal belts in industry: A position paper on their assets, liabilities, and use. *Am Indust Hygiene Assoc;* 54(12):752–554.

Mitchell LV, Lawler FH, Bowen D, Mote W, Ajundi P, Purswell J (1994). Effectiveness and cost-effectiveness of employer issued back belts in areas of high risk for back injury. *J Occup Med;* 36(1):90–94.

NIOSH (1994). Workplace use of back belts. Review and recommendations. U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. Cincinnati, OH; Publication No. 94–122.

Nirschl RP (1990). Patterns of failed healing in tendon injury, in Leadbetter WB, Buckwalter JA, Gordon SL (eds). Sports-Induced Inflammation. Park Ridge, IL: American Orthopaedic Society, pp 577–585.

OSHA (1995). Draft Ergonomics Protection Standard. U.S. Department of Labor, Occupational Safety and Health Administration. Washington, D.C. March, 1995

Ranney D (1993). Work-related chronic injuries of the forearm and hand: Their specific diagnosis and management. *Ergonomics;* 36(8):871–880.

Rempel D, Manejlovic R, Levinsohn DG, Bloom T, Gordon L (1994). The effect of wearing a flexible wrist splint on carpal tunnel pressure during repetitive hand activity. *J Hand Surg;* 19(1):106–110.

Spooner GR, Desai HB, Angel JF, Reeder BA, Donat JR (1993). Using pyridoxine to treat carpal tunnel syndrome. Randomized control trial. *Canadian Family Practice,* 39:2122–2127.

Stransky M, Rabin A, Leva NS, Lazaro RP (1989). Treatment of carpal tunnel syndrome with vitamin B-6: A double blind study. *Southern Med J;* 82(7):841–842.

Tubiana R, Thomine JM, Mackin E (1984). *Examination of the Hand and Upper Limb*. Philadelphia, PA: W.B. Saunders Co.

Upfal M (1994). Understanding medical management for musculoskeletal injuries. *Occup Hazards;* Sept:43–47.

Vallfors B (1985). Subacute and chronic low back pain; Clinical symptoms, absenteeism, and work environment. *Scand J Rehab Med;* Suppl 11:1–99.

Werner RA, Franzblau A, Johnston E (1994). Quantitative vibrometry and electrophysiological assessment in screening for carpal tunnel syndrome among industrial workers. *Arch Phys Med Rehabil;* 75:1228–1232.

WHO (1985) Identification and control of work-related diseases. World Health Organization Geneva: WHO Technical report; 174:7–11.

Wiesel SW, Feffer HL, Rothman RH (1984). Industrial low back pain, a prospective evaluation of a standardized diagnostic and treatment protocol. *Spine;* 9:199–203.

Wiesel SW, Boden SD, Feffer HL (1994). A quality based protocol for management of musculoskeletal injuries. *Clinical Orthopaedics and Related Research,* 301:164–176.

Wood DJ (1987). Design and evaluation of a back injury prevention program within a geriatric hospital. *Spine;* 12:77–82.

Available online at www.sciencedirect.com
SCIENCE DIRECT
Applied Ergonomics 34 (2003) 491–496
APPLIED ERGONOMICS
www.elsevier.com/locate/apergo

Ergonomics—Costs and Benefits Revisited

David Beevis*

Defence and Civil Institute of Environmental Medicine, 1133 Sheppard Avenue West, P.O. Box 2000, Toronto, Ontario M3M 3B9, Canada

Abstract

An earlier review reported a dozen cases where ergonomics applications had resulted in cost savings. A large number of publications which refer to the topics of the cost-effectiveness and cost–benefits of ergonomics can now be found. However, data showing the value of ergonomics applications remain scarce. Cost–benefit and cost-effectiveness studies are difficult to conduct for a number of reasons. While it is unlikely that the general case for the value of ergonomics can be proven, ergonomists must be in a position to discuss the potential costs and benefits of their work with clients. The Business case model is suggested as one way to structure an analysis of where a potential ergonomics application might reduce the risks to costs or the possibility of lost benefits.

Keywords: Ergonomics; Cost–benefit; Cost–effectiveness; Business case

1. Introduction

During the 1969 annual meeting of the Ergonomics Society, the late Miss I.M. Slade reported a few case studies on ergonomics costs and benefits and appealed to members for more data to illustrate the value of the discipline. In an attempt to broaden interest in the subject, the first Scientific Editor of Applied Ergonomics, Prof. B. Shackel, encouraged me to collaborate with I.M. Slade to conduct a more exhaustive review of ergonomics costs and benefits for publication. The paper by Beevis and Slade (1970) identified a dozen cases where ergonomics benefits had been expressed in financial terms.

The data that were found demonstrated financial benefits from the application of ergonomics in a number of areas: improvements to operator performance resulting from the redesign of equipment and working environments, reductions in the frequency of accidents and operator errors and reductions of the costs of the overall design effort due to the contribution made by ergonomists. The authors noted that assigning costs and benefits to ergonomics interventions could be extremely difficult. The authors also suggested that as ergonomists became more fully involved in the design of new tasks and equipment they would find it increasingly difficult to collect data on costs and benefits because there would be fewer cases that would provide comparative data. The paper concluded by questioning whether further evidence on the value of ergonomics was really necessary and suggested that ergonomists should concentrate on producing results that are understandable and obviously worthwhile rather than focusing on cost savings.

A recent search of Ergonomics Abstracts Online using the terms ‘cost effectiveness’ and ‘cost benefit’ identified more than thirteen hundred references. Therefore, it seems appropriate to review some of the conclusions of the 1970 paper.

2. Scarcity of data and difficulty of assigning costs and benefits

Despite the number of ergonomics references that use the terms cost–benefit or cost-effectiveness, data that illustrate the general case for the value of ergonomics are still scarce. Many references compare the costs of implementing different solutions to a particular ergonomics problem; they do not identify the cost savings to the system that is being improved. One reason for this is that benefits such as reduction in anticipated accidents or mistakes are difficult to assign and cost out (see, for example, Rouse and Boff, 1997). A complicating factor is that when ergonomics is an integral part of some larger improvement in capability or effectiveness, good

*Present address: 124 Bruton Street, Port Hope, Ontario, L1A 1V3, Canada.

0003-6870/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/S0003-6870(03)00068-1

operability is 'invisible' and its contributions cannot be separated out from the performance of components of a system or an item of equipment (Lane, 1987). It was for that reason that Beevis and Slade (1970) suggested that it would become increasingly difficult to collect data on costs and benefits.

In fact, few organizations study their operations in detail as long as they appear to be working satisfactorily. So cost and performance data are not readily available. For example, while trying to build a case for integrating the collection of injury and health statistics, MacDonald (2000) approached a number of large employers in Ontario for information on the costs associated with the occupational health and safety aspects of their operations. She found that most employers collect enough cost data to build a case for health and safety within their own organization, and then proceed on the assumption that it is financially beneficial. MacDonald concluded that the level of effort required to gather complete cost data is a major drawback to such efforts. "Seldom do companies spend the time and money required to accurately assess the cost of the problem. Instead, they put their resources into prevention initiatives" (ibid).

Even focused surveys require a great deal more effort than is normally available in the ergonomics or human factors community. To assist cost-effectiveness comparisons of competing training programmes, Kennedy and Jones (1992) recommended the use of iso-performance curves which show the relationship between personnel abilities measured on an aptitude scale and the time to train a given percentage of operators or maintainers up to an acceptable standard. They concluded that none of the data archived by the US Navy would support the generation of iso-performance curves and that additional effort would be required.

Because the benefits from an application usually accrue sometime after implementation of a change, the ergonomists responsible are seldom available to collect data on the effects of their work because they have to move on to other problems. Concerns about commercial confidentiality and the cost of the necessary data collection and analysis effort are also disincentives to developing case studies of costs and benefits. Furthermore, few potential clients of an ergonomics application are willing to support activities if there is doubt expressed about whether or not it will work. Proposals for collecting data on the benefits or effectiveness of an application can, and have, been interpreted as meaning that ergonomics may not work and is not worthwhile.

3. The general case for the value of ergonomics applications

The cases reported in Beevis and Slade (1970) covered a broad range of ergonomics applications. Examples included the redesign of the operator–machine interface. However, it was too early to expect many applications related to computer systems (although the paper did mention Whitfield's (1964) efforts to evaluate the benefits from the redesign of a computer). Nielsen (1993) addressed the case for applying ergonomics (or usability engineering in his terms) to computer systems. From a survey of 31 development projects he reported increase in productivity of 12% and paybacks on investment ranging from 200% to more than 500% for an average investment of 6% of the project budget.

Such inventories of benefits are, however, only one of four sets of evidence that are required to prove the general case for the value of ergonomics. As with any hypothesis, proof requires evidence in each cell of a 2×2 truth table based on whether ergonomics was applied or not, and whether cost savings occurred or not (Table 1). Reviews such as those of Beevis and Slade (1970) or Booher and Rouse (1990) provide evidence only for cases where ergonomics was applied and costs were reduced or effectiveness was improved.

Cases where ergonomics was not applied and costs were not saved and effectiveness was not improved have been reported quite often because they are the starting point for remedial ergonomics applications. Several of the examples mentioned in this paper fall into this category. In contrast, ergonomists are seldom in a position to collect data on cases where ergonomics was not applied and cost savings were achieved or effectiveness was improved. Finally, few cases have been reported where ergonomics was applied and did not provide cost savings or improve effectiveness.

Given this situation it seems unlikely that the ergonomics discipline, or any other, will be able to prove the general case for its value in cost terms. However, the individual ergonomist must be in a

Table 1
The four sets of information required to prove the general value of ergonomics

	Ergonomics was applied	Ergonomics was not applied
The project achieved improved effectiveness and/or reduced costs	A few cases have been reported	Ergonomists are seldom aware of such cases
The project did not achieve improved effectiveness and/or reduced costs	Such cases are seldom reported	Ergonomists have reported a large number of such cases

position to discuss the potential value of an ergonomics application.

4. Making the business case for a specific application

Beevis and Slade (1970) focused on cost savings from ergonomics applications. However, cost savings should not be the only potential financial benefit to be considered. The *business case* model uses three categories of financial benefit:

- Costs saved.
- Costs avoided.
- New opportunities.

Ergonomics applications can lead to *costs saved* in a number of ways; one is by identifying what the problem is that really needs to be solved. Zeff and Anderson (1964) surveyed the working environment of an electronics clean room following complaints of excessive noise. Following detailed measurements they concluded that the real cause of complaints of discomfort was the combination of temperature, humidity, and impermeable 'clean room' clothing that the employees were obliged to wear. MacDonald (2000) reported the case where a company implemented a wide variety of initiatives including upgrades of employee workstations, general and home safety programs, and first aid and 'ergonomics' training. Despite significant expenditures these changes had no apparent effect on lost-time injuries. The company then worked with their drug and extended health benefit provider to review data on the most frequent heath problem categories within their workforce. The review showed that the vast majority of prescriptions and benefit claims were related to stress. One year after developing and implementing a strategy to address stress, lifestyle, job-sharing, and work pace issues, there was a significant drop in lost time and improved morale and productivity.

Other studies have identified cost savings associated with human resources. A one-time investment in human factors, or ergonomics, has the potential for a high return because personnel costs, including training, are recurring (Price, 1990). Reflecting this, personnel and selection and training systems have been the focus of many attempts to save costs. A number of studies have reported comparisons of different training systems in terms of their cost to achieve a given performance criterion. For example, Magee (1984) investigated the training effectiveness of a video-disc based tank gunnery simulator. Trainers estimated that simulator training should reduce the number of rounds fired when training on the actual gun by 20 per trainee. Given the costs of the rounds, Magee concluded that the costs of the tank firing simulator would be recouped in the first training course. More recently, Magee also investigated the utility of a virtual-reality, helmet-mounted display for training ship conning skills which produced conning performance equal to that obtained from training on an actual ship (Magee, 1997) and which is 1% of the capital cost of a full bridge simulator (Magee, 2001).

Costs avoided are costs that might be anticipated in the future unless action is taken to avoid them. In the design of consumer goods, equipment or systems, cost avoidance concerns are associated with avoiding returns or loss of sales or clientele and with minimizing technical support calls, investigation of customer complaints, and use of help lines, etc. Identifying user requirements is another area where costs may be avoided because users do not always require the complexity that can be built into technology. For example, it has been reported that aircraft systems have become so complex that they contain features and modes of operation that most pilots do not use (Howells, 1984); the same is reported for software (Nielsen, 1993). The portions of training schemes that teach the intended user features that will not be used are an additional cost to the end user.

Ergonomics applications, whether to product design or to operations within an organization, can avoid a wide range of costs associated with human resources. Booher and Rouse (1990) provided an investment model for human resources which identifies several centres where costs may be avoided, including rejection rates through selection and training, injury and sickness, and price per unit based on job performance. Tighter matching of selection and training with task performance requirements can avoid the costs of training personnel who do not complete a full training course. For example, in the 1980s, 20% of women entering the Canadian Forces (CF) Mobile Support Equipment Operator trade and 10% of female candidates entering the CF Non-Trades Drivers course were failing part way through training. This resulted in significant 'lost' training expenditures. Research showed that these rejection rates could be improved by the modification of the size and strength selection standards for those trades (Celentano et al., 1982).

Many new systems introduce 'skill creep' by requiring higher levels of skill, experience and/or training than predecessor systems. For example, in 1988 the CF bought a towed remotely operated vehicle (ROV) at a cost of $955 000, to train reservists in mine hunting technology and maritime route survey operations. The ROV proved too complex for the intended use; it required more skill to operate than had been anticipated and it was necessary to establish a new training programme (Auditor General for Canada, 1992). If new equipment exploits existing operator skills, the costs of new training programmes can be avoided.

Maintaining skills once trained is also an area where there is potential for avoiding costs. Models of skill acquisition and retention (Rose, 1987) may enable the extent of initial training and the frequency and extent of subsequent practice to be predicted at the time that systems are being developed. For example, the weightings in Rose's model reflect the fact that memory for rigid procedures and fixed sequences of operation decays quite rapidly. Thus a design that avoids the need for the user to memorize complex procedures should suffer less skill decay than other designs.

For the business case *new opportunities* are associated with providing a new capability or expanding the market potential of a product or process. One way to do this is by providing the system with sufficient flexibility to meet new situations. The need for flexibility is, of course, why humans are retained in systems and why ergonomics is required in design. The only examples of such adaptability known to the author are from military systems where the operators have adapted to new situations, including operating with reduced manning. 'User acceptance' and 'Ease of use' can expand the market for products, particularly consumer goods. They can also contribute to the effectiveness of protective clothing and equipment by ensuring that it is worn and used properly. As an extension of this principle, ergonomics can contribute to the market potential of equipment and systems by ensuring that it is operable by the broadest possible range of users. User capabilities such as body size range, strength, dexterity, and vision and operator skills have all been shown to limit the range of potential users of equipment and systems.

5. The potential value of an ergonomics application

Beevis and Slade (1970) suggested that an emphasis on operator or system performance would avoid the difficulties or dealing with the problems of 'cost–benefit' and 'cost-effectiveness.' This change has come about much more slowly than anticipated in 1970, although a growing number of projects now use performance-based specifications and make selection or design decisions based on cost to achieve a specified level of performance. There is no lack of evidence that ergonomics applications can contribute to effectiveness in a number of areas, including operability, safety, reliability, maintainability, availability and survivability. However, one motivation for writing the 1970 (Beevis and Slade, 1970) paper was to provide evidence to meet the challenge often posed by potential clients or project managers to the effect "Why should I apply ergonomics on my project when it will take extra time and cost a lot? How is it cost-effective?" Unfortunately, ergonomists still experience this kind of reaction to their discipline.

In fact, cost–benefit analyses are complicated and difficult to conduct for any discipline (see, for example, Rouse and Boff, 1997). In many cases the potential client or manager who challenges the value of ergonomics is not in a position to provide the information required to conduct any kind of cost analysis. Cost-effectiveness analysis seeks to find the lowest-cost option to achieve a specified objective using criteria reflecting effectiveness which need not be expressed in financial terms; cost–benefit analysis seeks to achieve the greatest benefit, however defined, per unit cost, or a specified benefit at the lowest cost. Therefore, in order to evaluate a potential ergonomics application, the criteria used in the analysis must support the comparison of cost or of performance factors that include the effectiveness of the human–machine system, selection and training, customer support, as well as user acceptance of the system or equipment being designed (although user preference is sometimes included in cost-utility analysis, it is not a factor in cost-effectiveness). However, such human factors criteria are usually available only if an ergonomist or human factors specialist is employed to develop them.

It might be more appropriate to re-cast this issue in terms of risk. Boff (1990) suggests that risk is the potential for costs or lost benefits and typically represents a major source of uncertainty in any new complex system design. In that context, ergonomics can be considered part of a risk-reduction strategy. Some idea of the range of potential risks is given by a reverse engineering study conducted by the US Army on four systems that were in service (Promisel et al., 1985). Associated with a lack of human factors:

- Concepts of use were incomplete or ill-suited to the user.
- Personnel requirements were underestimated.
- Skills and abilities required were underestimated or undetermined.
- Training was untested.
- Training devices were unobtainable.

In order to provide a basis for discussion with potential clients or project managers, various benefits from ergonomics that have been identified above can be used to identify areas where risks of costs or lost benefits might occur in a given project, as shown in Table 2.

6. Conclusions

This paper was stimulated by the large number of references to ergonomics cost–benefits or cost-effectiveness now available compared with the number available for review in 1970. Nevertheless, most of the conclusions from that earlier review appear to remain unchanged. While there are reports on the cost–benefit or cost-effectiveness of ergonomics applications, comparatively few studies provide detailed information on the costs and benefits, or improvements in effectiveness from

Table 2
Benefits associated with specific ergonomics activities

Ergonomics intervention	Costs saved	Costs avoided	New opportunities
Identify user requirements	√	√	√
Define operational, support, and maintenance concepts	√	√	√
Identify and control factors that limit operator performance	√	√	
Identify user functions and tasks	√	√	√
Identify and control excessive operator workload	√	√	
Provide an acceptable working environment	√	√	√
Identify and control excessive operator stress	√	√	
Identify and implement user population stereotypes		√	√
Design for full range of potential users (gender, size, strength, vision, clothing, etc.)		√	√
Develop for user acceptability		√	√
Develop for flexibility of use			√
Reduce opportunity for operator error	√	√	
Reduce need for user manuals	√	√	√
Reduce requirements for new skills	√	√	√
Reduce likelihood of skill decay	√	√	√
Reduce personnel requirements	√	√	√
Develop lowest-cost training system (capital and/or operational costs)	√	√	
Improve personnel selection system	√	√	
Contribute to personnel retention	√	√	
Reduce time lost through accidents or injuries	√	√	

ergonomics applications. Cost–benefit studies are difficult to conduct for any discipline and it remains very difficult to assign costs and benefits to ergonomics applications. Furthermore many potential clients are unable to provide the necessary data and unwilling to support a thorough study of costs and benefits.

The increased emphasis on functionality and effectiveness that was hoped would avoid the difficulties of identifying costs and benefits is occurring only slowly. Thus, while the general case for the value of ergonomics is extremely difficult to prove, ergonomists must be able to discuss potential benefits with clients and project managers. The three categories of costs saved, costs avoided and new opportunities that are used to develop a business case can provide a structure for discussing where a potential ergonomics application might reduce the risk of costs or loss of anticipated benefits.

References

Auditor General for Canada, 1992. Report of the Auditor General of Canada to the House of Commons, Government of Canada, Ottawa (Chapter 18).

Beevis, D., Slade, I.M., 1970. Ergonomics—costs and benefits. Appl. Ergon. 1 (2), 79–84.

Boff, K., 1990. Meeting the challenge: factors in the design and acquisition of human-engineered Systems. In: Booher, H.R. (Ed.), Manprint: An Approach to Systems Integration. Van Nostrand Reinhold, New York.

Booher, H.R., Rouse, W.B., 1990. MANPRINT as the competitive edge. In: Booher, H.R. (Ed.), MANPRINT: An Approach to Systems Integration. Van Nostrand Reinhold, New York.

Celentano, E.J., Nottrodt, J.W., Saunders, P.L., Noy, I.M., MacDonald, G.A.H., 1982. Anthropometric and strength requirements for Canadian Forces trades personnel: selection standards for MSEOP (935), WT(L) (421) and WT(A) (571) Trades. Report No. 82-R-51, Defence and Civil Institute of Environmental Medicine, Toronto, Ontario (Restricted—Defence Purposes Only).

Howells, H., 1984. Panel II Summary. In: Merriman, S. (Ed.), Proceedings, NATO DRG Panel-8 Workshop on Applications of Systems Ergonomics to Weapon System Development, Vol. 2. NATO Defence Research Group, Brussels.

Kennedy, R.S., Jones, M.B., 1992. Simulating the impact of MPTS trade-off decisions by application of Isoperformance Methodology. Essex Corporation Report. Naval Training Systems Center, Orlando, FL.

Lane, N.E., 1987. Evaluating the cost-effectiveness of human factors engineering. Institute for Defense Analysis Contract MDA 903 ’84 C 0031. Essex Corporation, Orlando, FL.

MacDonald, H., 2000. Scoping study: human systems integration accident database. Report DCIEM-CR-2000-090, MacDonald Associates Consulting Report. Defence and Civil Institute of Environmental Medicine, Toronto, Ont.

Magee, L.E., 1984. The training effectiveness of a videodisc-based trainer for the Leopard C1. Report No. 84-R-76, Defence and Civil Institute for Environmental Medicine, Toronto, Ont.

Magee, L.E., 1997. Virtual reality simulator (VRS) for training ship handling skills. In: Seidel, J., Chatelier, P.R. (Eds.), Virtual Reality, Training’s Future? Perspectives on Virtual Reality and Related Emerging Technologies. Plenum Press, New York.

Magee, L.E., 2001. Personal communication. Defence and Civil Institute of Environmental Medicine, Toronto, Ont.

Nielsen, J., 1993. Usability Engineering, San Diego, CA: Academic Press.

Price, H.E., 1990. Conceptual system design and the human role. In: Booher, H.R. (Ed.), MANPRINT: An Approach to Systems Integration. Van Nostrand Reinhold, New York.

Promisel, D.M., Hartel, C.R., Kaplan, J.D., Marcus, A., 1985. Reverse engineering: human factors, manpower, personnel and training in the weapon system acquisition process. Report ARI-TR-659, Army

Research Institute for the Behavioral and Social Sciences, Alexandria, Virginia.
Rouse, W.B., Boff, K.R., 1997. Assessing cost/benefits of human factors. In: Salvendy, G. (Ed.), Handbook of Human Factors and Ergonomics. Wiley, New York, pp. 1617–1622.
Rose, A.M., 1987. Acquisition and retention of skills. In: McMillan, G., Beevis, D., Salas, E., Strub, M., Sutton, R., van Breda, L. (Eds.), Applications of Human Performance Models to Equipment Design. Defense Research Series, Vol. 2. Plenum Press, New York.
Whitfield, D., 1964. Validating the application of ergonomics to equipment design: a case study. Ergonomics 7.2, 165–174.
Zeff, C., Anderson, D.M., 1964. Environment study of the clean room. Psychological Memo No.145, EMI Electronics Ltd., Feltham, Middlesex.

Applied Ergonomics 35 (2004) 427–441

APPLIED ERGONOMICS

www.elsevier.com/locate/apergo

A participatory ergonomics intervention to reduce risk factors for low-back disorders in concrete laborers

Jennifer A. Hess*, Steven Hecker, Marc Weinstein, Mindy Lunger

Labor Education and Research Center, 1289 University of Oregon, Eugene, OR 97403-1289, USA

Received 5 August 2003; received in revised form 23 March 2004; accepted 20 April 2004

Abstract

Construction laborers rank high among occupational groups with work-related musculoskeletal injuries involving time way from work. The goals of this project were to: (1) introduce an ergonomic innovation to decrease the risk of low-back disorder (LBD) group membership, (2) quantitatively assess exposure, and (3) apply a participatory intervention approach in construction. Laborers manually moving a hose delivering concrete to a placement site were evaluated. The hypothesis tested was that skid plates would prevent hose joints from catching on rebar matting, and the hose would slide more easily. This would decrease the need for repetitive bending and use of excessive force.

Four laborers were evaluated wearing the Lumbar Motion Monitor (LMM), a tri-axial electrogoniometer that records position, velocity and acceleration. Workers were measured during three comparable concrete pours. Worker perceptions of the innovation utility and exertion were surveyed.

During initial use of skid plates, flexion increased significantly ($p<0.001$) while velocity, acceleration and moments did not change. After implementing a worker modification, low back velocity, acceleration and moments were significantly reduced ($p<0.05$). Reductions in these factors have been associated with decreased risk of belonging to an occupational group with LBDs. Use of secured skid plates during horizontal concrete hose movement may in part decrease the risk of LBD group membership among concrete laborers. Crew participation resulted in skid plates being a more effective intervention. The LMM is a promising tool for quantitative assessment in construction.

Keywords: Ergonomics; Construction; Low-back disorder risk; Trunk kinematics; Workplace interventions

1. Introduction

Construction workers are at significant risk of work-related musculoskeletal injury (Schneider 2001, Silverstein et al., 2002), and within this group construction laborers in particular are at risk. Construction laborers perform many physically demanding tasks including cleaning and preparing construction sites, digging trenches, operating power tools, tending machines, loading and unloading building materials, and mixing and placing concrete. These activities expose workers to ergonomic risk factors such as awkward postures, frequent heavy lifting, repetitive motions, and hand/arm and whole body vibration (Everett, 1997). Consistent with this, in construction strains and sprains are the most common type of work-related, nonfatal injury, accounting for over 37 percent of all injuries resulting in days away from work (CPWR, 2002). In 2000 construction laborers ranked fourth among all occupational groups in the number of work-related musculoskeletal injuries involving time way from work and first in lost workdays; construction laborers had a median of 10 days away from work compared to a median of 7 days for all industries (BLS, 2000). Twenty-two percent of lost-time injuries among laborers are due to overexertion, and construction laborer is the highest risk occupation for work-related back pain (Ringen and Seegal, 1995; Guo et al., 1995). In Washington State between 1990 and 1994, 31.5 percent of workers'

*Corresponding author. Tel.: +1-541-346-3073; fax: +1-541-346-2790.

E-mail address: jhessdc@earthlink.net (J.A. Hess).

0003-6870/$ - see front matter
doi:10.1016/j.apergo.2004.04.003

compensation claims by union construction laborers were for strains and sprains, and concrete construction was among the top ten risk classifications rated by incidence rates (Schneider, 2001).

1.1. Applied biomechanics emphasis

There have been a number of studies demonstrating the association between occupational factors and low-back disorders (LBD) (Biering-Sorensen, 1984; Troup et al., 1987; Battié et al., 1990; NIOSH, 1997). In construction the pouring of concrete is a job that poses substantial risks of low-back musculoskeletal injury to laborers due to the weight of the material, awkward postures assumed by workers, schedule pressures driven by the time-sensitive nature of the material, and sometimes harsh environmental conditions. Yet there are few rigorous field-based studies among construction workers in general and laborers specifically, that evaluate the dynamics of the low back or quantify the effect of ergonomic modifications on exposure risk for LBD.

The construction industry has a distinctive work structure and culture that makes conducting such rigorous field-based research challenging. Each construction site possesses unique characteristics such as management philosophy, crew composition, weather, site constraints, and building design that make comparison across sites impractical. Even within one site it can be difficult to compare an innovation across time, as building construction is a process of constant transition. Work crews may be on a site for only a few days or weeks and within a crew, workers may change on a daily basis, depending on supervisory decisions. Craft workers develop their work practices through a socialization process in which apprentices learn from more experienced members of the craft. There is a craft identity and attitude toward problem solving as well as the use of tools and work methods (Jensen and Kofoed, 2002). Therefore, for a new tool or piece of equipment to be readily adopted it must be easy to use, easy to learn to use, and it must fit within the craft culture. Otherwise, potential long-term benefits may never be realized because the innovation may not be given a fair chance due to time pressures of the job and time required for familiarization (Cederqvist and Lindberg, 1993; Jensen and Kofoed, 2002). Time pressures also mean that the work is fast paced and uninterruptible, minimizing the time researchers can interact with workers to test and attach data collection equipment.

Because of these difficulties, past studies of ergonomics in construction have mainly used observational evaluations, surveys of worker perception or lab studies in simulated environments (Wiktorin et al., 1993; Buchholz et al., 1996; Spielholz et al., 1998; Hollmann et al., 1999; Chaffin et al., 1999). While these tools provide useful information, they have shortcomings. For example, observational studies are limited to evaluations of posture and the frequency with which an activity is performed using a static 'snapshot' of an activity. This provides no information about dynamic aspects of a task over the duration of the activity. Perception data is limited due to its subjective nature. The artificial work environments created in laboratory simulations may limit generalizations to the actual job and task applications as performed on a construction site. As new biomechanic assessment tools, such as electromyography, electrogoniometers and telemetry evolve, it is becoming possible to apply quantitative measurements to the evaluation of work activities among construction workers during actual fieldwork. Use of biomechanic tools in real work situations, such as in this study, provides greater insight into the dynamics of the low back and the complex nature of work-related back injury among construction workers.

1.2. Participatory model

Evidence from construction and other industries suggests that the involvement of end users is a key to successful implementation of ergonomic changes (Nora and Imada, 1991; Schurman et al., 1994; Brown, 2002; Koningsveld et al., 1998). Workers have unique knowledge about the jobs they do and in many instances they know valid solutions to ergonomic problems. Further, involving workers in ergonomic decisions builds trust, commitment and good will, which leads to increased job satisfaction and ultimately improved performance (Brown, 2002). Moir and Buchholz (1996) provide other compelling reasons why a participatory approach may be essential in construction. The dynamic nature of the workplace, in which workstations are regularly constructed and deconstructed, requires that those doing the work be intimately involved in decisions about and implementation of ergonomic changes. Construction workers have greater autonomy than most other groups of employees and because their workplace changes so constantly, solving problems is an integral part of their job. While this talent is most often applied to solving production problems, it is equally applicable to safety problems. Finally, to improve the chances of acceptance it is important to include the economic and cultural values of both workers and contractors in designing interventions. (Moir and Buchholz, 1996).

There are many approaches to worker participation that can be used to address ergonomic issues (Brown, 2002; Koningsveld, 1998). In this study the principles of co-operative inquiry (Reason, 1994) guided our applied construction ergonomics research. In contrast

to traditional biomedical research models in which researchers determine and exclusively control all elements of the intervention and research design, co-operative
inquiry explicitly acknowledges and incorporates the notion that research subjects can substantively contribute ideas and through their own behavior impact the ultimate success of the intervention. The model of co-operative inquiry encourages researchers and participants to mutually recognize respective areas of expertise. Consistent with this, there may be times that researchers bring new ideas to the field, and when this is done, participants are encouraged to provide feedback and to suggest modifications. Our adaptation of the co-operative inquiry model is both pragmatic and consistent with the normative assumptions guiding the engagement of labor in organizational processes. We recognize that the ultimate success of ergonomic interventions depends not only on the efficacy of a given change in work practices in reducing musculoskeletal risk, but also on the willingness of workers and employers to utilize new work practices in the field. This, in turn, requires that the proposed change in work practice appears reasonable to those who are asked to utilize it and that it be consistent with the efficiency concerns of all stakeholders in the construction project. Worker and contractor collaboration in selecting and modifying researcher-initiated ergonomic interventions contributes to both of these aims.

In his discussion of the co-operative inquiry model, Reason (1994) identifies four phases of applied research that we incorporated into our applied ergonomics research: (1) researchers and participants agree on an area of inquiry, (2) researchers and subjects collaborate in the selection of an initial change in work practice designed to ameliorate the identified risk, (3) 'full immersion,' in which workers implement the proposed ergonomics intervention, and (4) researchers and workers collaborate to develop, implement, and assess worker-initiated modifications.

This study utilized a participatory ergonomics intervention designed to identify and implement equipment and work practice modifications to reduce ergonomic risk factors in concrete placement work. Our university-based research team collaborated with a construction contractor and concrete laborer crew in developing and implementing the intervention. The intervention had three specific goals: (1) to assess changes in low-back exposure among concrete laborers, after introduction of a specific ergonomic tool; (2) to evaluate whether participation by laborers in selection and application of the tool would lead to a more effective reduction of risk exposure; and (3) to field test an instrument that could quantitatively assess exposure risk among construction workers.

2. Methods

2.1. Study setting

This study was conducted during the construction of a $40-million four-story office and classroom building on a university campus. The intervention evaluated was use of skid plates by concrete laborers for horizontal movement of concrete-filled hoses. Due to the construction plan for this building, pouring concrete from above was not a possibility because four stories of decking were in place prior to concrete placement, requiring laborers to manipulate a concrete-filled hose from the concrete truck to the placement site on each floor. With the exception of the ground floor, the concrete-filled hose lays upon iron rebar matting and must be pulled and repositioned as the work progresses. Each section of hose was 4 m long and 8 cm in diameter. Hose sections were joined together by a quick release latch that was difficult to pull over rebar matting, causing workers to use excessive force to move the hose. At the beginning of concrete placement there may be as many as eight sections of hose attached to the slick line, depending upon the distance to the pumper. As the concrete pour progresses the hose has to be moved back and out of area where concrete is being placed. The laborer at the head of the hose (lead hoseman) verbally signals workers to move the hose. Laborers work as a team to pull the hose away from the newly poured concrete. The laborer crew typically moved the hose by pulling on a 100–125 cm long piece of rope attached to the hose at the couplings and at points half way between these joints.

The ergonomic intervention was the introduction of skid plates, 60 cm diameter metal disks (Conforms, www.conforms.com, part # LH-54) that can be placed under the couplings between sections of hose. Four skid plates were placed under hose couplings near the pour end of the hose dispensing concrete. We hypothesized that skid plates would reduce stress to the low back by preventing the hose couplings from catching on rebar matting and by decreasing the overall friction of pulling the hose. This would reduce the need for repetitive bending and use of excessive force to dislodge, pull and move the hose. All laborers were invited to participate in the intervention and in accordance with university requirements for research involving human subjects, participation was not compulsory and those who participated provided written informed consent.

2.2. Participatory process

We applied the four phases of the co-operative inquiry model (Reason, 1994) to our ergonomic intervention with construction laborers. In the *first phase*, researchers and participants agree on an area of inquiry.

Initially we met with the project superintendent and foremen to discuss which jobs and trades they were concerned about on this site, with regard to LBDs. In construction, as elsewhere, this is an important place to start since buy-in by management is essential to the success of any type of intervention. It was not possible to involve craft workers themselves at this stage because they were not yet present on the project. After discussion of a number of trades and job tasks on this site, the job task of most concern to the contractor from past experience was the horizontal manipulation of the hose that delivers concrete from the concrete truck to the placement site. Pouring from above was not possible due to overhead obstructions.

In the *second phase*, researchers and subjects collaborate in selecting the tool or work practice that would be changed to attempt to ameliorate the identified risk. A critical part of this phase is the opportunity for workers to share their experiences, ideas, and concerns regarding the proposed intervention and the project. In some instances, this could lead to a change in the newly proposed work practice prior to the initiation of the intervention; in other cases the proposed intervention may proceed unaltered, though workers' initial response to the proposed change may provide clues as to possible later modifications that might be incorporated into the fourth phase of the co-operative inquiry. As part of this effort, our research team conducted a focus group with concrete laborers. We met with the crew of 10 laborers and presented a review of basic ergonomic principles and common risk factors associated with musculoskeletal injuries to supplement workers' knowledge and to provide a context for discussion about aspects of moving concrete hose that place them at risk for low back injury. We discussed with the project superintendent and foremen potential solutions that would reduce LBD risk during hose movement, but no one had specific suggestions in mind.

From past experience conducting construction research we have learned that often workers are hesitant to suggest ergonomic solutions, especially if the solution costs money or could impact productivity. The climate among construction management is often to 'take it or leave it.' Since construction workers can be replaced at a moment's notice, they typically believe it is better to keep quiet than to complain about working conditions. Additionally, the pace with which construction proceeds influences the ability of researchers to intervene and collect data. In this study, once discussions with the project superintendent and foremen identified concrete work performed by laborers as a potentially hazardous task for the low back, we had approximately three weeks to meet with laborers, gain their support for an intervention, decide on the intervention, design the study and implement the intervention. The work schedule was such that once concrete placement began we had only 6–8 weeks until it concluded. Therefore, we came to the focus groups prepared to discuss one or more potential problems and armed with a number of potential ergonomic solutions. After discussing various aspects of their work, laborers agreed that movement of concrete hose was a difficult, potentially hazardous task but they could think of no remedies. Since no solutions to this problem were forthcoming, we proposed the adoption of skid plates to both management and laborers. Neither management nor the laborer crew were not aware of skid plates, but they were interested and enthusiastic to try them.

The *third phase* is "full immersion," in which workers implement the proposed ergonomic intervention. An essential aspect of this third phase is an assessment of the intervention. As in the other phases of co-operative inquiry, the desire for collaboration between researchers and subjects does not preclude, but requires, an explicit recognition of the specific expertise each party brings to the research project. In this study we contributed the expertise necessary to design, implement and quantitatively assess the efficacy of the intervention, namely skid plates. For their part, workers gained experience using the new tool so that they could provide input on its effectiveness and/or suggest modifications to enhance its effectiveness.

The experience gained in the full immersion phase provides the basis for the *fourth phase* of the collaborative inquiry in which the researchers and workers collaborate to develop, implement, and assess worker-initiated modifications or 'field fixes'. During this phase, the locus of innovation in the development of improved ergonomic tools and work practices shifts from the researcher to the workers in the field, while the responsibility for the evaluation of the intervention remains with the research team. In this case, researchers met informally with laborers during a lunch break to gather their opinions after using the skid plates on several 5-h concrete pours. Additionally, following assessment of the intervention with the field fix (securing skid plates to hose), researchers met once again with the laborer crew to get feedback on the effectiveness of the intervention after the field fix was introduced.

The development of our co-operative inquiry model for applied ergonomics research in the construction industry is an integral part of our effort to apply rigorous research to the validation and adoption of improved tools and work practices by workers and contractors. Practitioner engagement helps ensure that the ergonomic innovations initiated in phases two and three and the subsequent field modifications developed in phase four are workable in the field. Beyond this, worker engagement in the development of these ergonomic solutions enhances the likelihood that modified worker practices will continue to be used on the site and will be introduced on new worksites.

2.3. Measurement apparatus

To measure the worker's lumbar region posture, motion, and force, we used the Lumbar Motion Monitor (LMM), a portable tri-axial electrogoniometer developed at Ohio State University (Marras et al., 1993). The LMM glides between a set of harnesses, one strapped to the low back and one between the scapulae, and allows collection of data during work activities. It collects time and position data in the lumbar region, in three planes, at 60 Hz via an analog-to-digital converter and transmits the information via digital telemetry to a laptop computer.

The mass of the concrete-filled hose was measured using a Chatillon 300-strength dynamometer (Ametek, Largo, FL) by lifting it vertically one foot off the ground. Trials were video taped using a digital camcorder. Frequency of pulling the hose was estimated by two researchers timing each of the four volunteers, in 10-min increments, at each of the three data collection times. One worker was measured on only two occasions. These results were then averaged to provide an estimate of overall hose pulling frequency. The frequency of laborers moving hoses was observed for over 30 h both before and during data collection, and we felt confident that a sufficiently representative number of frequency observations were collected.

2.4. Procedure

All 10 laborers on the crew participated in focus groups and informal discussions. Seven laborers agreed to fill out questionnaires. Five laborers volunteered to be evaluated using the LMM. This number was decided upon for two reasons. First, based on findings by Allread et al. (2000) in manufacturing, evaluation of three trials in three workers was found to be sufficient to acquire valid results. The second reason was pragmatic. Given the time sensitive nature of pouring concrete, we were only able to place the LMM on workers during lulls in the work. It took 45–60 min per worker to gather data, making it impractical to collect data on more than four or five subjects. All 10 laborers were given the opportunity to volunteer to be measured. All participants were right-handed, healthy males with no current low-back complaints. Data were collected during three different concrete pour times in the following order:

(1) Baseline: Before the introduction of the skid plates laborers pulled and moved hoses in the usual manner;
(2) Hose lying unsecured on skid plates: In this condition skid plates were used as suggested by the manufacturer; and
(3) Skid plates with worker modification: In this condition workers remedied limitations they identified with the skid plates and incorporated a 'field fix' intended to increase the effectiveness of the skid plate (Fig. 1).

Fig. 1. Laborer pulling concrete-filled hose secured to skid plate.

On this site concrete placement of floors, requiring horizontal movement of hoses, was divided into sections. Pours were scheduled to occur 2–3 days each week over a period of 6–8 weeks. Pouring concrete began at 5 a.m. and lasted 4 to 6 h, until the section was finished. To minimize threats to internal validity, such as muscle fatigue and temperature changes, data collection commenced when pouring began in the morning. We attempted to minimize order effects by evaluating volunteers in a random order, so that no person was always the first or last to be assessed. Additionally, volunteers also rotated between the front, middle and back of the hose, since this was a standard part of the work controlled by the foreman to prevent fatigue. For our purposes it served to increase the generalizability of skid plate use.

Approximately 20 trials were recorded for each worker at each time interval as they pulled and moved the hose. Therefore, for a single worker, trials contain data from pulls at different positions on the hose. The LMM was sized to fit the worker and then calibrated while still in its box. When it was his turn, and during a lull in the work, each laborer stepped away from the hose to have the LMM strapped to his low back and chest. The lower harness was placed so that the top of the belt was at the L5/S1 junction while the upper harness fit between the scapulae. Data collection for each trial commenced when the lead hoseman verbally signaled workers by yelling 'pull' and ended when the researcher, sitting nearby at the computer, saw that the worker wearing the LMM was no longer pulling on the hose rope. Each trial was between 1 and 10 s long and the average trial time was 4.2 s, although the actual time a worker pulled the hose was shorter.

A brief survey of worker perceptions was completed at the time of the second focus group meeting. After data collection, but while still using skid plates, laborers were asked to complete a Borg exertion scale (Borg, 1982) to estimate overall pulling exertion with and without skid plates. The Borg is a validated scale that has been used for many years in sports to measure perceptions of exertion. This study used the 15-point scale where 6 is considered a very, very light exertion, and 20 is considered a very, very hard exertion. The original Borg 15-grade scale (from 6 to 20) of exertion has been shown to be a good method for evaluating simple applications of perceived exertion (Borg, 1982). Completion of the Borg was done during the post data collection focus group, which occurred 3 weeks after data collection but during a time when laborers were still using skid plates.

2.5. Data analysis

This study used a quasi-experimental pretest–posttest design in which subjects served as their own controls. To analyze the effectiveness of skid plates utilized per manufacturer specifications and with the worker-recommended field fix, we regressed dummy variables representing different workers and different levels of the intervention on a series of dependent biomechanical variables provided by the LMM. Twelve to 15 trials per subject were analyzed at each of the three test intervals.

The LMM Ballet™ software provided output data in two forms. 'Motion data' files provide time, position, angular velocity (ω) and angular acceleration (α) for rectified data at each collection point, in each trial. Therefore, in a 4-s trial collected at 60 Hz there would be $60 \times 4 = 240$ data points, and there were 12–15 trials per subject for each level of the intervention. For each trial in the motion data, the maximum and average values for position, velocity and acceleration in each plane are placed into a 'summary data' file. Position data are reported such that neutral position, recorded when the LMM was calibrated in its box, equals zero, which may or may not correspond to zero when placed on a worker, depending on their personal lordosis. Right-sided moments are positive while extension and left-sided movements are negative. Additionally, Ballet™ predicts the risk of LBD group membership associated with the measured task, based upon a model developed and validated by Marras et al. (1993). For each variable (e.g. sagittal flexion, maximum lateral velocity) the model finds the maximum value across all trials for an individual. These values are then averaged across subjects to predict the overall low-back disorder risk associated with a particular task.

Due to the fast pace and restricted working conditions it was not possible to measure pulling force during actual hose pulls. Changes in the maximum external moment occurring about the lumbar spine with and without skid plate use were calculated using the relationship between linear and angular acceleration and the equation:

$$a = \sqrt{(r\omega^2)^2 + (r\alpha)^2}, \tag{1}$$

where a is the linear acceleration and r the perpendicular distance between the force pulled and the low back, measured from L5/S1 to a place just above the elbow. In this way the magnitude of tangential linear acceleration was estimated for each trial. Force to the low back was then calculated using Newton's second law

$$F = ma. \tag{2}$$

Mass is the vertical weight of the concrete-filled hose. Moments in each of the three planes were estimated using the equation

$$M = Fd. \tag{3}$$

Distance (d) is the average perpendicular distance measured from the laborer's hands to the low back. This model makes three assumptions: (1) the body is a rigid link segment model, (2) the laborer's arms are rigid so that the moment arm does not change during the pull and (3) calculation of tangential linear acceleration is a reasonable reflection of measured angular acceleration.

3. Results

3.1. Worker descriptive statistics

Four laborers completed the evaluation with the LMM, 10 laborers participated in focus groups while seven laborers answered a short questionnaire. Laborer characteristics are presented in Table 1. The average age of the four laborers measured was 35 years compared to 39 years for the entire crew. The average length of experience in concrete work was 4.8 years for the four evaluated laborers and 8.2 years for the entire crew. The

Table 1
Laborer descriptive information

Subject	Height (cm)	Weight (kg)	Age (years)	Years doing concrete work
S01SB	185	83.9	24	7
S02JM	175	77.1	40	9
S05KW	175	86.2	47	6
S06MT	175	90.7	28	6
Participant average	178	84.4	35	4.8
Crew average ($n = 7$)	180	88.1	39	8.2

crew average is high because one laborer had been doing concrete placement work for 28 years. If this laborer is removed, the average for the remaining six laborers is 4.9 years. Laborers pulled or moved the concrete hose on average 1.8 times per minute (108.6 times per hour), with a range of 1.2–2.9 times per minute. Most of the time activity was steady, making this estimate an accurate reflection of the job frequency. Yet in any given hour there may have been 10–15 min of down time, for example while waiting for another concrete truck or unclogging the hose. During those times laborers may have removed sections of the hose, carried them out of the work area, performed other tasks as needed, or taken a short break. The average duration of floor pours on this site was 4–6 h. The mass of the concrete-filled hose measured with the dynamometer was 36.3 kg for a force of 356 N.

3.2. Skid plate use and crew perceptions

The skid plates have a cradle in which the hose sits. However, when laborers pulled the hose with their ropes the hose frequently came out of the cradle and off the skid plates. After using the skid plates for one complete pour laborers decided it was necessary to secure the hose couplings in place. After some discussion several types of tie-downs were tried: (1) two rubber bungee cords across the hose, (2) nylon strapping with a quick tighten and release mechanism, and (3) rebar tying wire. Laborers felt that wire worked the best, the bungees were adequate, but the strapping did not hold the hose securely.

Six crewmembers liked using the skid plates after they had the opportunity to tie down the hose and would use them again while one, the youngest and least-experienced laborer, did not like them. Six of the seven laborers found that the skid plates required less pulling effort. Since frequent bending is a risk factor for low-back injury, worker perceptions of bending were solicited. Two laborers thought that using the skid plates required more bending, four thought it was the same, while one thought there was less bending. Six workers felt the skid plates made their work easier. Seven laborers completed a Borg exertion scale. The average exertion score without using skid plates was 14 (hard) while the average score using skid plates was 11.9 (fairly light).

3.3. Lumbar Motion Monitor results

The means and standard deviations for the 18 kinematic variables, and lumbar moments, are presented in Table 2. Standard deviations are high, but are consistent with values recorded by Marras et al. (1993) in manual material handlers. In the sagittal plane most kinematic variables initially increased after introducing the skid plates but then decreased substantially after workers secured the hose. For example, flexion increased from 6.67° to 13.88° upon using the skid plates but then decreased to 4.76° when the hose was tied down. Also, velocity and acceleration increased slightly with initial skid plate use, but decreased once the hose was secured. In the frontal plane, use of skid plates decreased right bending, while in the transverse plane it reduced twisting to the right. Again, once the hose was secured there were additional decreases in mean velocity and acceleration. The mean maximum moment in all three planes decreased with skid plate use while further decrease was noted after securing the hose. The greatest change was in twisting movements where the moment decreased from 35.22 Nm without skid plates to 27.23 Nm using secured skid plates. The peak maximum moment recorded was 120.76 Nm in flexion, decreasing to 100.35 Nm when the hose was secured to the skid plates.

3.4. Regression analysis

Kinematic data and estimates of low-back moments were regressed to assess the relative impact of skid plates on injury risk, for both unsecured and secured skid plate use. Two dummy variables represent use of skid plates with no tie-down and use of skid plates with tie-downs, while pulling the hose without skid plates is represented in the base of the model. To control for individual differences, three person dummy variables are included in the model so that individuals served as their own controls.

Ballet™ software calculates 18 measures encompassing average and maximum position, velocity, and acceleration, but not all are relevant for analysis of this intervention. Since injury risk was evaluated using the LBD risk model, the two kinematic variables used in this model, maximum lateral velocity and average twisting velocity, were assessed. The movement laborers used to move the concrete hose across rebar matting was most commonly a combination of trunk extension, started from a flexed position, right-sided bending, and right-twisting. NIOSH (1997) suggests that work-related awkward postures are associated with the risk of low-back injury, while Marras and Mirka (1989, 1990) have demonstrated that asymmetric motions coupled with acceleration increase spinal loading. Given these relationships and the fact that all four volunteers were right-handed, measures of right-sided bending and twisting, plus flexion and extension, were evaluated. High forces have also been associated with low-back injury (NIOSH, 1997). In this study acceleration was used to estimate low-back force in three planes during hose pulling. Overall, nine measures encompassing position, motion, and force were assessed for the task of pulling concrete hose by laborers. Table 3 shows the linear regression

Table 2
Descriptive statistics for low-back kinematic and kinetic variables

Variable	No skid plate $n = 68$		Skid plate $n = 48$		Secured skid plate $n = 78$	
	Mean (SD)	Min/max	Mean (SD)	Min/max	Mean (SD)	Min/max
Sagittal plane						
Max flexion (deg)	6.67 (8.54)	−12.99/35.38	13.88 (15.81)	−10.46/54.28	4.76 (11.52)	−11.20/39.27
Max extension (deg)	−7.05 (6.33)	−19.80/18.80	−4.32 (7.24)	−14.8/17.7	−7.94 (5.91)	−18.40/21.00
AP range of motion (deg)	13.72 (8.76)	0.00/41.91	18.20 (15.91)	0.39/58.28	12.69 (9.57)	0.01/43.24
Max velocity (°/s)	28.50 (16.548)	0.02/78.07	32.76 (24.12)	2.65/115.91	23.69 (17.07)	0.08/67.83
Ave velocity (°/s)	7.51 (4.16)	0.01/23.06	7.71 (5.08)	0.27/27.92	6.03 (3.83)	0.04/17.74
Max acceleration (°/s^2)	224.72 (137.89)	0.22/584.13	225.24 (151.20)	26.29/880.58	173.54 (124.72)	0.98/610.26
Frontal plane						
Max left bend (deg)	−1.31 (6.37)	−14.43/21.24	−2.22 (5.36)	−16.46/10.20	−1.33 (4.44)	−20.66/8.41
Max right bend (deg)	7.86 (4.16)	−3.15/22.38	7.67 (6.23)	−2.53/24.51	5.89 (3.80)	−3.21/14.07
ML range of motion (deg)	9.18 (5.45)	0.10/21.80	9.90 (7.62)	0.10/29.2	7.22 (6.38)	0.00/30.00
Max velocity (°/s)	26.00 (17.27)	0.46/93.00	24.26 (17.19)	0.98/77.64	18.04 (13.82)	0.20/58.42
Ave velocity (°/s)	6.12 (3.81)	0.23/18.41	5.26 (3.20)	0.49/11.74	4.23 (3.41)	0.10/14.54
Max acceleration (°/s^2)	185.82 (123.89)	5.46/701.85	174.15 (118.91)	10.32/559.14	134.04 (104.02)	2.51/448.71
Transverse plane						
Max left twist (deg)	−3.88 (6.78)	−16.48/14.67	−4.05 (7.99)	−19.30/13.31	−3.33 (7.03)	−22.59/11.50
Max right twist (deg)	8.18 (7.81)	−12.87/28.72	7.26 (6.04)	−7.79/18.36	6.28 (7.87)	−17.83/24.12
Twist range (deg)	12.06 (9.09)	0.01/41.58	11.30 (8.34)	0.00/31.52	9.61 (8.65)	0.07/40.64
Max velocity (°/s)	35.03 (24.56)	0.05/103.79	30.07 (18.39)	0.00/63.60	26.66 (20.85)	0.47/112.15
Ave velocity (°/s)	7.35 (5.79)	0.03/29.77	5.51 (4.00)	0.00/16.05	4.72 (3.85)	0.14/16.93
Max acceleration (°/s^2)	273.55 (193.74)	0.61/843.09	224.13 (142.50)	0.00/560.86	204.91 (162.28)	5.38/981.04
Moments						
Max lateral moment (Nm)	24.32 (17.45)	0.72/83.18	21.48 (14.13)	1.53/61.40	17.72 (14.53)	0.33/73.62
Max AP moment (Nm)	29.56 (20.18)	0.02/96.25	28.22 (19.19)	3.34/120.76	24.40 (21.43)	0.13/100.35
Max twisting moment (Nm)	35.22 (24.90)	0.08/119.59	27.85 (17.86)	0.00/81.84	27.23 (22.25)	0.71/112.84

results for these variables comparing skid plate use, with and without the tie-down, to no skid plate, when controlling for individual differences. For position variables, the degree of maximum flexion was not statistically significantly different when using secured skid plates compared to no skid plates. However, there was significantly greater flexion among laborers pulling the hose using unsecured skid plates ($p < 0.001$). Extension, as would be expected with greater amounts of flexion, was significantly decreased when workers used unsecured skid plates ($p < 0.05$). Also, when workers tied the hose to the skid plates there was a significant decrease in the amount of maximum right-sided bending ($p < 0.01$), although no difference was found in maximum right twisting. In terms of velocity, maximum lateral velocity and average twisting velocity decreased

Table 3
Regression results for kinematic variables controlling for individual differences (unstandardized coefficients with standard errors in parentheses)

$N = 200$	Constant (SE)	Skid (SE)	Secure skid (SE)	Person 1 (SE)	Person 2 (SE)	Person 3 (SE)	F-statistic	DF	Adj. R^2
Max flexion	0.276 (1.782)	7.733*** (2.074)	−2.203 (1.794)	13.279*** (2.064)	5.384* (2.226)	7.293*** (2.200)	12.810***	18	0.234
Max extension	−8.019*** (1.051)	3.029* (1.223)	−0.944 (1.058)	2.258† (1.217)	−0.144 (1.312)	1.493 (1.297)	2.954*	18	0.048
Max right bend	7.523*** (0.685)	0.781 (0.797)	−2.033** (0.690)	1.371† (0.793)	−3.662*** (0.856)	2.357** (0.846)	11.789***	18	0.218
Max right twist	4.725*** (1.171)	−0.373 (1.363)	−1.944 (1.179)	4.362** (1.356)	3.435* (1.462)	6.407*** (1.446)	4.818***	18	0.090
Max lateral velocity	16.374*** (2.365)	0.504 (2.752)	−8.149*** (2.381)	13.536*** (2.739)	6.154* (2.953)	18.717*** (2.919)	12.079***	18	0.223
Ave Twist velocity	6.095*** (.734)	−1.187 (0.854)	−2.663*** (0.739)	1.748* (0.851)	−0.559 (0.917)	3.382*** (0.906)	6.761***	18	0.130
Max AP acceleration	165.131*** (20.802)	−4.311 (24.206)	−54.213** (20.943)	136.146*** (24.097)	80.027** (25.982)	35.625 (25.681)	8.495***	18	0.163
Max lateral acceleration	113.941*** (17.142)	1.704 (19.947)	−53.333** (17.258)	105.373*** (19.857)	56.289** (21.411)	128.626*** (21.162)	11.105***	18	0.207
Max twist acceleration	217.967*** 26.680	−26.551 31.047	−69.545** 26.861	69.152* 30.906	2.853 33.324	138.926*** 32.938	5.731***	18	0.109

† $p<0.10$.
* $p<0.05$.
** $p<0.01$.
*** $p<0.001$.

Table 4
Regression results for lumbar moments, controlling for individual differences (unstandardized coefficients with standard errors in parentheses)

$N = 193$	Constant (SE)	Skid (SE)	Secure skid (SE)	Person 1 (SE)	Person 2 (SE)	Person 3 (SE)	F-statistic	DF	Adj R^2
Max frontal moment (Nm)	15.572** (2.209)	−1.330 (2.571)	−7.082* (2.224)	19.967** (2.559)	3.369 (2.759)	10.829** (2.727)	15.459**	188	0.273
Max sagittal moment (Nm)	21.808** (2.802)	−1.746 (3.260)	−5.923* (2.821)	26.677** (3.245)	4.601 (3.499)	−0.447 (3.459)	18.485**	188	0.312
Max axial moment (Nm)	29.095** (3.431)	−4.876 (3.992)	−8.470* (3.454)	6.911** (3.974)	−4.714 (4.285)	9.370* (4.235)	7.356**	188	0.141

* $p<0.05$.
** $p<0.001$.

significantly when workers used secured skid plates compared to not using skid plates ($p<0.001$). Acceleration for anterior–posterior (AP), lateral and twisting movements also decreased significantly using secured skid plates compared to not using skid plates ($p<0.01$). When comparing workers one, two, and three to worker four, there were statistically significant individual differences between workers ($p<0.10$ to $p<0.001$).

Forceful movements are factors associated with risk of low-back injury, especially when considered in relation to asymmetric lifts or rapid speeds (Fathallah et al., 1998). Table 4 shows results from a linear regression of lumbar spine moments. Lumbar region torque decreased significantly in all three movement planes when workers used secured skid plates compared to not using skid plates ($p<0.05$). For two laborers individual differences were statistically significant.

3.5. LBD risk model

Risk of LDB group membership was calculated using Ballet™ software and peak kinematic data, peak moment estimates and pulling frequency in these laborers (Fig. 2). In this model the interaction of five variables—lifting frequency, maximum sagittal flexion, maximum lateral velocity, average twisting velocity, and lumbar moment—were found to be the best predictors of risk of a job leading to low-back injury (Marras et al., 1993). Marras et al. (2000) determined the probability that a job would be a member of a group of jobs found to have high numbers of LBD. The risk of LBD group membership was rated as high (⩾70 percent), medium risk (30–70 percent) or low (⩽30 percent). The overall probability of risk of LBD group membership decreased from 67 percent prior to skid plate use to 46 percent when using secured skid plates. Lifting frequency did not change with skid plate use and remained constant at

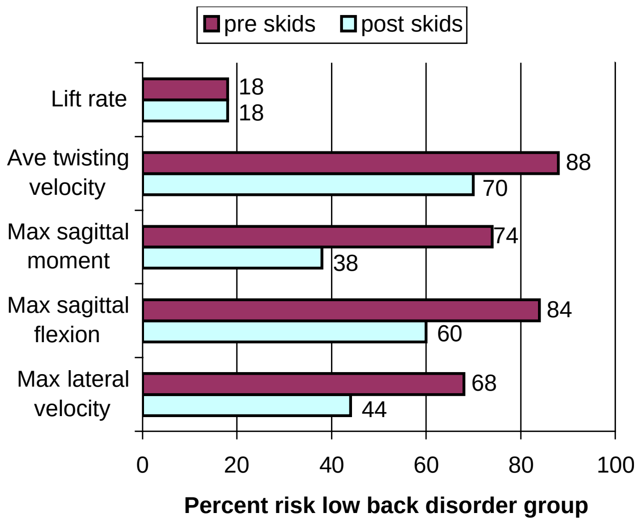

Fig. 2. Risk of LBD group membership model before skid plate use and with secured skid plates.

1.8 lifts per minute. Average twisting velocity, maximum lateral velocity, and maximum sagittal flexion all decreased the risk for LBD group membership. When using secured skid plates, maximum lateral velocity decreased from 68 percent to 44 percent risk, maximum sagittal flexion also decreased 24 percent, while average twisting velocity demonstrated the least change by decreasing only 18 percent with use of secured skid plates. The greatest reduction was in sagittal lumbar moment, which decreased from 74 percent to 38 percent with use of secured skid plates.

4. Discussion

4.1. Low-back biomechanics and LBD group risk

As results from biomechanical studies become available, it is evident that in addition to manual handling of heavy loads and repetitive activities, asymmetry and motion effects such as trunk velocity and acceleration and, more importantly, the interactions among these factors, are integral to understanding injury risk (McGill and Hoodless, 1990; Mirka and Marras, 1990; Marras et al., 1993; Fathallah et al., 1998). The present study evaluated the interactions among these factors. Use of secured skid plates decreased flexion an average of 2°. Mean asymmetric motion in right-sided bending and right-sided twisting also decreased an average of 2° in each plane. The mean maximum velocity decreased by 4.81°/s during AP movements, 7.96°/s with lateral movements, and 8.37°/s with twisting movements. Even though these are statistically significant decreases, if taken individually the magnitudes may not be substantial. However, Marras and Mirka (1989, 1990) and Mirka and Marras (1990) demonstrated the importance of interactions among these variables. For example, as trunk asymmetry in the transverse plane increases, trunk strength decreases and the external load shifts from the erector spinae muscles to less capable and smaller oblique muscles (Marras and Mirka, 1992). Trunk strength also decreases as velocity increases. Additionally, the degree of flexion interacts with velocity and asymmetry. Trunk strength is greatest when flexed at 22.5° and decreases with more or less flexion. The upshot is that more muscle activity is required to maintain the same level of force production, resulting in additional loading of the spine.

Asymmetric motions have been shown to create significant compressive and shear forces to the lumbar joints (McGill and Hoodless, 1990), while others have demonstrated substantial levels of compressive and anterior and lateral shear loads at the L5/S1 joint caused by the interaction of velocity and asymmetry during lifting (Fathallah et al., 1998). The interaction of these factors may result in damage to facets and the intervertebral disc (Shirazi-Adl, 1989, 1991). In the current study, pulling the hose involved varying degrees of asymmetry in conjunction with moderate amounts of force prior to skid plate use. These laborers employ movement patterns with sufficient asymmetry, velocity, and force to result in large compressive and shear forces in the low back. Skid plate use decreased workers' asymmetry and velocity, and calculations from acceleration data suggest that low-back torque was also reduced, potentially decreasing L5/S1 loading.

The low back is also affected by the interaction between asymmetry and acceleration. Marras and Mirka (1990) demonstrated that as acceleration and asymmetry increase, so does muscle activity in low-back agonists and antagonists. Even with a torque of only 4.1 Nm, in some conditions muscles are activated up to 50 percent of their maximum to produce angular accelerations. It seems likely that large amounts of muscle activation, and in particular coactivation, may reflect significant increases in spinal loading during larger trunk torque generation. In the present study, without skid plates the average maximum acceleration was 185.82°/s^2 in lateral motions, 224.73°/s^2 in AP motions and 273.55°/s^2 in twisting motions. These amounts decreased by 51.77°/s^2 for lateral movements, 51.19°/s^2 for AP motions, and 68.64°/s^2 for twisting motions with use of secured skid plates. Considering the level of muscle activation that occurs in conjunction with rapid accelerations during asymmetric movements, decreasing these factors is an important aspect of decreasing LBD risk, if for no other reason than to decrease muscle fatigue and the accompanying risk of overexertion injury.

Skid plates did not affect pulling frequency. Yet, these findings are contradictory to those found by Fulmer

(2002) when evaluating skid plate use at a large Boston highway construction project. He found that laborers using skid plates increased their 'no lift time' by 15 percent. They also decreased the number of lifts higher than 1 ft but increased the number of small lifts less than 1 ft from the ground. He attributed these findings to the hose being easier to move thereby allowing laborers to make additional corrections in hose placement without lifting it. These contradictions may be accounted for by differences in methodology. Fulmer used PATH, (Buchholz et al., 1996) an observational sampling method, and sampled the entire job performed by the concrete laborers. This technique may have provided a more comprehensive assessment of the laborer's job, whereas our study was limited to evaluation of one task, pulling hoses.

Mean sagittal flexion did not change significantly with secured skid plate use, although the risk associated with maximum sagittal flexion, based on the LBD model, which uses peak values, decreased by 24 percent. This reflects the dynamics of variable interaction as opposed to findings from strictly evaluating the magnitude of individual factors. Flexion actually increased significantly when using non-secured skid plates, underscoring the importance of worker feedback.

Taken individually, the changes in asymmetry, velocity, and acceleration measured using secured skid plates, while statistically significant, may not be meaningful. The interactions between asymmetric postures, velocity, acceleration, and force increase the risk of injury because of the large trunk moments created in association with decreased available strength. During dynamic activities a substantial portion of back strength goes to support and move the trunk, resulting in less strength capacity for lifting, pulling, or otherwise moving an object. The net result is an increased risk for injury. Seen in this context the interactions of these motion variables combined with worker characteristics such as lumbar moment, suggest that the changes observed using skid plates translate into the potential for decreased injury risk during hose movement.

Actual low-back injury rates among concrete laborers still need to be linked to skid plate use. Because laborers perform many different duties and come and go from a work site, collecting injury incidence data over an extended period that are specific to a particular activity or group of workers is impossible. Therefore, we are forced to draw conclusions from data gathered from other types of workers. Marras et al. (2000) correlated decreases in risk of LBD group membership with decreases in injury incidence following ergonomic interventions in over 36 manual material handling (MMH) jobs in 16 different companies. They found that for jobs in the medium LBD risk category, a decrease in risk from 67.2 percent to 50.7 percent corresponded to a decrease in injury incidence rate from 11.0 to 4.3 per 100 full time employees. Using the same model, the present study found a similar LBD job risk in laborers pulling concrete hoses that decreased from 67 percent to 46 percent. We cannot conclude that this drop in risk would result in a significant reduction in injury incidence, especially considering the wide variety of activities laborers routinely perform, but it is reasonable to assume that the application of secured skid plates to the hose-pulling task by laborers is one component of decreasing their overall risk of low-back injury associated with this job task.

4.2. Fit of the risk model

Concrete laborers repetitively (108.6 times/h) pull hoses that weigh 36.3 kg across rebar matting for up to 6 h a day. It is reasonable to ask if this activity is similar enough to the repetitive movement activities evaluated in manual material handlers to apply the LBD risk model. Few studies have evaluated the biomechanics of pulling, and three-dimensional dynamic models are needed to fully understand the constraints imposed upon the spine during pulling activities. Current models of pulling consider only low-back compression and the interaction of the foot with the floor when pulling carts, and there is no consensus as to which factors are most important (Chaffin et al., 1999). Arguably, these pulling models do not adequately fit the activity of pulling hoses by laborers. When pulling hoses, laborers started from a slightly flexed posture and extended from the low back in order to reposition a concrete-filled hose. This task, like those of MMHs, is dynamic in nature, consisting of rapid movements and repetitive bending combined with substantial force production in the L5/S1 region during movement of a mass.

In terms of dynamic factors, the MMHs measured by Marras et al. (1993) had, on average, faster peak velocities and accelerations in all planes, and workers flexed and extended to a greater degree than did the concrete laborers. They evaluated over 450 jobs from 61 different industries, from such diverse jobs as automobile assembly, machined products manufacturing, handling clothing, glass production, electronic equipment manufacturing, and food processing. An analysis of task variability found that the majority of variability in trunk motions was due to work task design and that variation due to repeated cycles or different employees was small (Allread et al., 2000). Even so, they demonstrated the predictive ability of the LBD model for this wide variety of dynamic MMH activities (Marras et al., 1993, 2000). It therefore seems reasonable to use the LBD model for assessing pulling activities among concrete laborers.

According to Mirka et al. (2000) a shortcoming for applying the LBD risk model is its reliance upon repetitive jobs performed continuously throughout the day in job cycles of 1 min or less. Therefore, characteristics of non-repetitive jobs may not be represented in the model predictions. Concrete laborers perform largely non-repetitive activities, in that they poured concrete only 2 days a week, for 4–6 h a day and moved hoses at a rate of 1.8 pulls/min. Yet within this timeframe their job is fairly repetitive and only one repetitive task of their job, pulling hoses, was evaluated. Thus, if we accept the validity of the LBD risk model, we could conclude from our data that if concrete laborers performed the hose pulling task all day every day, their LBD risk is moderate and is significantly reduced by the use of secured skid plates. Since these workers do other tasks as well, we cannot reach this conclusion without some analysis of the low-back risk posed by those other tasks. Some other laborer tasks would be amenable to analysis with the LMM, e.g. shoveling, but others may not be. This again points to the challenge of ergonomic exposure assessment among construction workers. In fact, it is precisely the variation in tasks and cycle times of much construction work that makes the LMM attractive because it collects real-time exposure measures. But at the same time its limitation is that its validity may apply only to parts of the individual worker's job. Further research to fully characterize low-back disorder risk in construction workers could build on the Task-Based Exposure Assessment Model developed for airborne contaminants (Susi et al., 2000).

4.3. Worker and contractor involvement

The importance of worker and supervisor involvement in the successful adaptation of ergonomic tools has been widely reported (Moir and Buchholz, 1996; Nora and Imada, 1991). In this situation the first step was support from the construction superintendent and his willingness to invest financially and philosophically in trying a new intervention. The superintendent appreciated the impact of musculoskeletal injuries in construction and identified concrete laborers as among those workers he felt were at the greatest risk. Several other trade groups and tool possibilities were explored before settling on the use of skid plates with these workers. While the superintendent knew of no alternatives to pulling concrete-filled hoses, when shown a picture of skid plates he was immediately enthusiastic, feeling that they could reduce friction associated with moving hoses across rebar matting. When asked why these devices had not previously been used, his reply was that he was unaware of their existence, and that he had not supervised jobs in recent years that required horizontal movement of concrete hose.

Crew involvement in the use of skid plates led to modifications that made the tool more useable and effective. Due to the time pressures of concrete pouring, the superintendent initially instructed workers to seat the hose on the skid plates but not attach them. However, laborers became frustrated because the hose frequently pulled out of the skid plate cradle, requiring workers to bend and lift more often in order to reposition the hose. An informal discussion with the laborers indicated they thought the hose should be secured to the skid plates. The three tie-down methods that were tried came from discussions with the crew and received approval from the superintendent. The straps took too long to attach and didn't hold the hose securely enough. The bungee cords worked reasonably well but were too elastic. The preferred method was the rebar wire that could be quickly attached to the skid plate handles and removed with wire cutters when sections of hose were removed. Laborers found the skid plates helpful at some times and hose positions but a hindrance at others. When placed at the pouring end of the hose, the skid plates were less efficient because of the frequent need to remove hose sections. Workers found them most useful several sections from the pour end of the hose.

As part of enhancing worker involvement in the adoption of skid plates and overall musculoskeletal injury reduction, researchers discussed the biomechanic findings from preliminary data analysis and individual body mechanics. Workers were able to see video of their own work practices during concrete placement and critique their activities. Quantitative information about worker low-back dynamics was used to address specific biomechanic factors and provide a dynamic dimension to body mechanics training beyond evaluations of static posture. For example, average twisting velocity decreased from 88 percent to 70 percent in the LBD risk model but still presents considerable risk. Using feedback on movement velocity during body mechanics training targets a component of the job task that until now has not been addressed and that could lead to further reductions in injury risk.

The challenges of making changes in construction practice, described in the introduction, make it particularly important to address the applicability of a research intervention to the 'real world' of construction. All aspects of the implementation and evaluation process require both supervisory support and crew involvement to maximize effectiveness. This case illustrates some of the differences between construction and fixed industry in terms of how participation is invited and organized. Timing is critical and researchers or ergonomic practitioners must be creative in accessing craft workers and finding collaborative opportunities. The role played by the researchers in this study eliciting worker and contractor input about worksite changes to improve ergonomics, introducing new tools, and getting worker feedback on effectiveness or modifications could be played by a safety coordinator, superintendent, or other supervisory personnel. Supervisors may need some training, both in ergonomic fundamentals and in particular techniques of eliciting ideas and evaluating impact, but their knowledge of the work and the crew gives them an advantage in integrating these processes into the work itself.

4.4. LMM utility

In order to evaluate ergonomic interventions in construction, evaluation techniques are needed that can capture the dynamic aspects of worker activities in real work situations. For these concrete laborers the LMM was an effective field tool for evaluating work activities beyond static postures or worker perceptions. The LMM telemetry worked flawlessly, enabling researchers to observe workers at a distance while gathering very accurate and specific position, velocity, and acceleration data for the low back. The process of strapping the LMM on laborers and removing it after data collection took only in a few minutes, minimizing disruption of work activities. Laborers were able to move about without restriction and did not find the LMM cumbersome. One concern was that the 'spine' of the LMM had a tendency to pop out of the upper harness when laborers fully flexed to the floor. This was dealt with by slightly lowering the upper harness, making the unit more secure in the harness.

Another strength of the LBD risk model is the relationship between injury rates and quantifiable dynamic trunk motion characteristics during actual work activities. The application of the LMM to field construction tasks among laborers or other crafts has not previously been reported in the literature and presents new insight into worker movement dynamics and job risk. The LMM would be difficult to use with other construction workers wearing large tool belts or harnesses, but there are undoubtedly modifications that could be made in some cases.

4.5. Limitations and future areas of inquiry

In field studies there are limitations that require certain assumptions to be made. In this study, in order to calculate low-back force we assumed that the average perpendicular distance from the workers' arms to their back was constant. In reality this distance could vary depending on worker position. However, we observed workers for many hours and noted that laborers consistently fixed their arms in a position close to their trunk. Also, for each worker, the moment arm was measured several times at different data collection times and the averaged results were consistent.

Because trial length varied from 1 s to 10 s, the possibility exists for bias based on the variation in trial length. A regression analysis controlling for length of trial time found no significant differences in outcomes based on time ($p < 0.05$).

Marras et al. (2000) calculated moments in the lumbar spine using a two-dimensional linear model by multiplying the mass of lifted objects by the maximum horizontal distance of the object in the worker's hands from the lumbar spine. Since pulling is a more complex motion, calculations of low-back torque were made using acceleration data. The transformation of angular acceleration to linear acceleration assumes that these two measures are similar. Our moment estimates are meant to provide a measure of the changes in low-back force over the different test times, rather than a reflection of absolute moment values.

An alternative hypothesis for our findings is the effect of learning to use skid plates. We attempted to address this issue by conducting a *t*-test comparing the first half of the trials, across all three data collections, with the last half of the trials. While we cannot conclude there was no learning effect across trial times, our analysis demonstrated no learning effect between the first and last half of data collection trials, suggesting that the changes noted were due to the effect of the skid plates alone.

Finally, the question remains as to whether the levels of velocity, acceleration, and torque found here actually lead to injury among concrete laborers. Correlation of these results with injury data would be helpful for better understanding this relationship. However, since workers come and go from a site with regularity and a job may last from a few days to months, gathering this type of data in construction has thus far eluded researchers.

5. Conclusions

In this study an ergonomic innovation to decrease low-back disorder risk among concrete laborers was introduced and evaluated using a quantitative instrument, the Lumbar Motion Monitor (LMM), which captures the dynamic aspect of job tasks. The LMM proved to be an effective field tool for use among construction laborers. With unsecured skid plates flexion, velocity, and acceleration increased, but when workers attached them to concrete-filled hoses the probability of risk of a low-back disorder decreased significantly. The variables most influenced by skid plate use were low-back moments, lateral velocity, and sagittal flexion. Most workers liked using the skid plates and thought they decreased the exertion of pulling hoses. Worker involvement and feedback were important for increasing the effectiveness of the skid plates. Future studies are needed to better understand the dynamics of pulling activities, to quantify other aspects of laborers' jobs, and to establish a relationship between changes in risk factors and actual incidence of low-back injury.

Acknowledgements

This study was funded by the National Institute for Occupational Safety and Health (NIOSH) through The Center to Protect Workers Rights (CPWR), NIOSH grant no. U02/CCU317202.

References

Allread, W.G., Marras, W.S., Burr, D.L., 2000. Measuring trunk motions in industry: variability due to task factors, individual differences, and the amount of data collected. Ergonomics 43 (6), 691–701.

Battié, M.C., Bigos, S.J., Fisher, L.D., Spengler, D.M., Hansson, T.H., Nachemson, A.L., Wortley, M.D., 1990. The role of spinal flexibility in back pain complaints within industry, a prospective study. Spine 15 (8), 768–773.

Biering-Sorensen, F., 1984. Physical measurements as risk indicators for low-back trouble over a one-year period. Spine 9 (2), 106–119.

BLS, US Department of Labor, 2000. Lost-worktime injuries and illnesses: characteristics and resulting time away from work, 2000. Bureau of Labor Statistics News Release, USDL 02-196 (http://stats.bls.gov/iif/home.htm).

Borg, G., 1982. Psychophysical bases of perceived exertion. Med. Sci. Sports Exercise 14 (5), 377–381.

Brown, O., 2002. Macroergonomic methods: participation. In: Hendrick, H.W., Kleiner, B.M. (Eds.), Ergonomics, Theory, Methods and Applications. Lawrence Erlbaum Associates, Mahwah, NJ (Chapter 2).

Buchholz, B., Paquet, V., Punnett, L., Lee, D., Moir, S., 1996. PATH: a work sampling-based approach to ergonomic job analysis for construction and other non-repetitive work. Appl. Ergon. 27 (3), 177–187.

Cederqvist, T., Lindberg, M., 1993. Screwdrivers and their use from a Swedish construction industry perspective. Appl. Ergon. 24 (3), 148–157.

Center to Protect Worker's Rights (CPWR), 2002. The Construction Chart Book. The US Construction Industry and Its Workers, 3rd Edition. Silver Springs, MD, www.cpwr.com, Chapter 36.

Chaffin, D.B., Andersson, G.B.J., Martin, B.J., 1999. Occupational Biomechanics, 3rd Edition. Wiley-Interscience, New York, Chapter 8, pp. 315–354.

Everett, J.G., 1997. Ergonomic Analysis of Construction Tasks for Risk Factors for Overexertion Injuries. Center for Construction Engineering and Management, University of Michigan, NTIS Publication No. PB97-207179, Ann Arbor, MI.

Fathallah, S., Marras, W.S., Parnianpour, M., 1998. An assessment of complex spinal loads during dynamic lifting tasks. Spine 23 (6), 706–716.

Fulmer, S., 2002. 15th Annual Occupational Safety and Health Institute Conference, COEH. Ergonomics UPS and Downs & Path, Berkley, CA.

Guo, H.R., Tanaka, S., Cameron, L.L., Seligman, P.J., Behrens, V.J., Ger, J., Wild, D.K., Putz-Anderson, V., 1995. Back pain among workers in the United States: national estimates and workers at high risk. Am. J. Ind. Med. 28 (5), 591–602.

Hollmann, S., Klimmer, F., Schmidt, K.H., Kylian, H., 1999. Validation of a questionnaire for assessing physical work load. Scand. J. Work, Environ. Health 25 (2), 105–114.

Jensen, L.K., Kofoed, L.B., 2002. Musculoskeletal disorders among floor layers: is prevention possible? Appl. Occup. Environ. Hyg. 17 (11), 797–806.

Koningsveld, E.A.P., Vink, P., Urlings, I.J.M., de Jong, A.M., 1998. Reducing Sprains and Strains in Constructions Through Worker Participation. The Center to Protect Workers' Rights, Washington, DC, 2001.

Marras, W.S., Mirka, G.A., 1989. Trunk strength during asymmetric trunk motion. Hum. Factors 31 (6), 667–677.

Marras, W.S., Mirka, G.A., 1990. Muscle activities during asymmetric trunk angular accelerations. J. Orthop. Res. 8 (6), 824–832.

Marras, W.S., Mirka, G.A., 1992. A comprehensive evaluation of trunk response to asymmetric trunk motion. Spine 17 (3), 318–326.

Marras, W.S., Lavender, S.A., Leurgans, S.E., Rajulu, S.L., Allread, W.G., Fathallah, F.A., Ferguson, S.A., 1993. The role of dynamic three-dimensional trunk motion in occupationally related low back disorders. Spine 18 (5), 617–628.

Marras, W.S., Allread, W.G., Burr, D.L., Fathallah, F.A., 2000. Prospective validation of a low-back disorder risk model and assessment of ergonomic interventions associated with manual materials handling tasks. Ergonomics 43 (11), 1866–1886.

McGill, S.M., Hoodless, K., 1990. Measured and modelled static and dynamic axial trunk torsion during twisting in males and females. J. Biomed. Eng. 12, 403–409.

Mirka, G.A., Marras, W.S., 1990. Lumbar motion response to a constant load velocity lift. Hum. Factors 32 (4), 493–501.

Mirka, G.A., Kelaher, D.P., Nay, T., Lawrence, B.M., 2000. Continuous assessment of back stress (CABS): a new method to quantify low-back stress in jobs with variable biomechanical demands. Hum. Factors 42 (2), 209–225.

Moir, S., Buchholz, B., 1996. Emerging participatory approaches to ergonomic interventions in the construction industry. Am. J. Ind. Med. 29, 425–430.

National Institute for Occupational Safety and Health (NIOSH), 1997. Musculoskeletal disorders and workplace factors, DHHS (NIOSH) publication no. 97-141. Government Printing Office, Washington, DC, US.

Nora, K., Imada, A.S. (Eds.), 1991. Participatory Ergonomics. Taylor & Francis, London.

Reason, P., 1994. Three approaches to participative inquiry. In: Denzin, N.K., Lincoln, Y.S. (Eds.), Handbook of Qualitative Research. Sage Publications, Thousand Oaks, CA.

Ringen, K., Seegal, J., 1995. Safety and health in the construction industry. Annu. Rev. Public Health 16, 165–188.

Schneider, S.P., 2001. Musculoskeletal injuries in construction: a review of the literature. Appl. Occup. Environ. Hyg. 16 (11), 1056–1064.

Schurman, S., Silverstein, B., Richards, S., 1994. Designing a curriculum for health work. Occup. Med. State Art Rev. 9, 283–304.

Shirazi-Adl, A., 1989. Strain in fibers of a lumbar disc: analysis of the role of lifting in producing disc prolapse. Spine 14 (1), 96–103.

Shirazi-Adl, A., 1991. Finite-element evaluation of contact loads on facets of an L2–L3 lumbar segment in complex loads. Spine 16 (5), 533–541.

Silverstein, B., Viikari-Juntura, E., Kalat, J., 2002. Use of a prevention index to identify industries at high risk for work-related musculoskeletal disorders of the neck, back and upper extremity in Washington State, 1990–1998. Am. J. Ind. Med. 41, 149–169.

Spielholz, P., Wiker, S.F., Silverstein, B., 1998. An ergonomic characterization of work in concrete form construction. Am. Ind. Hyg. Assoc. J. 59, 629–635.

Susi, P., Goldberg, M., Barnes, P., Stafford, E., 2000. The use of a Task-Based Exposure Assessment Model (T-BEAM) for assessment of metal fume exposures during welding and thermal cutting. Appl. Occup. Environ. Hyg. 15 (1), 26–38.

Troup, J.D., Foreman, T.K., Baxter, C.E., Brown, D., 1987. The perception of back pain and the role of psychophysical tests of lifting capacity. Spine 12 (7), 645–657.

Wiktorin, C., Karlqvust, L., Winkel, J., 1993. Validity of self-reported exposures to work postures and manual materials handling. Scand. J. Work Environ. Health 19 (3), 208–214.