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A Strategy for Industrial Power Hand Tool Ergonomic Research — Design, Selection, Installation, and Use in Automotive Manufacturing

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DHHS (NIOSH) Publication No. 95–114

Proceedings of a NIOSH Workshop

"A Strategy for Industrial Power Hand Tool Ergonomic Research—Design, Selection, Installation, and Use in Automotive Manufacturing"

January 13-14, 1994
Cincinnati, OH

U.S. Department of Health and Human Services
Public Health Service
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

August 1995

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DHHS (NIOSH) Publication No. 95-114

FOREWORD

The National Institute for Occupational Safety and Health (NIOSH) conducts research to identify, measure, analyze, and control occupational hazards. One NIOSH research priority is the control of work-related musculoskeletal disorders. An important step in controlling these disorders is to understand the dose-response relationship between the activity and the injury or illness. This document presents the proceedings of a NIOSH workshop that addressed duplication of power hand tool research, possible research gaps, and a cohesive research strategy for the automotive manufacturing industry. These proceedings contain a summary of conclusions from each workshop session, recommendations for effective information gathering, a possible research strategy, and an updated review of current research knowledge. Although the workshop emphasized the automotive manufacturing industry, other industries should find the session results, information gathering outline, and strategy useful when addressing topics related to power hand tools and work-related musculoskeletal disorders.

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Problem Source Identification Session

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ACKNOWLEDGMENTS

This document was prepared by the Division of Physical Sciences and Engineering (DPSE), Dennis M. O'Brien, Ph.D., Director. The contributions from the panel moderators, session recorders, panel members, and steering committee is gratefully acknowledged. In addition, we wish to thank Dr. Robert Radwin for developing the "white paper."

We also wish to thank the following NIOSH employees for providing advice, logistical support, and assistance in the preparation of the workshop and proceedings: Rosalynd J. Kendall, Heather K. Houston, Maggie A. Ivory, Debra A. Lipps, Bernice L. Clark, Deanna L. Elfers, Dennis M. O'Brien, Phillip A. Froehlich, Amy Beasley-Spencer, Gary S. Earnest, Ronald M. Hall, Daniel R. Farwick, Paul A. Hentz, Roger Wheeler, Anne Votaw, Vanessa Becks, and Anne Stirnkorb.

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WORKSHOP SUMMARY

BACKGROUND

The Engineering Control Technology Branch (ECTB) of the National Institute for Occupational Safety and Health (NIOSH) initiated a project entitled the "Ergonomic Study of Power Hand Tools in the Automotive Manufacturing Industry" to address the issue of upper extremity work-related musculoskeletal disorders (WMSDs)[1]. The following are some reasons for focusing on the association between WMSDs and power hand tool use in manufacturing:

- The use of power hand tools in modern industry for repetitive, manual work is widespread.
- The best tool for a specific task is often not obvious, because there is such a large variety of power hand tools to choose from.
- Automation is usually not an alternative to work performed with power hand tools.
- Work involving power hand tools often combines several WMSDs risk factors (i.e., vibration, force, posture, contact stress, and repetitive motion).
- Workers who use power hand tools often spend a large portion of the workday holding and operating them.
- Some power hand tools are capable of producing very high forces.
- There is a high incidence of WMSDs in manufacturing industries today, particularly in industries using power hand tools.

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[1]The term work-related musculoskeletal disorders (WMSDs) includes musculoskeletal, neuromuscular, as well as neurovascular tissue injury and illness.

- An understanding of fundamental ergonomic aspects of power hand tool use is needed.

- Power hand tool manufacturers and industries using power hand tools are beginning to recognize the importance of ergonomics in power hand tool design, selection, installation, and use.

Industries involved with manually intensive assembly tasks present an increased risk of WMSDs to the labor population. According to the Bureau of Labor Statistics (BLS) 1992 data, manufacturing industries accounted for two-thirds of all newly reported occupational illnesses. A majority of those cases were disorders associated with repeated trauma (approximately 282,000). Typically, many of these manufacturing tasks include power hand tools.

In automotive manufacturing, the need to complete a high number of precision tasks in a timely manner often involves the extensive use of power hand tools. Also, in the 1991 BLS report, the automotive manufacturing industry had one of the greatest illness incidence rates of new cases of disorders associated with repeated trauma at 558 per 10,000 full-time workers, third only to meat and poultry processing (BLS 1993).

As a result of these problems, automotive manufacturers and tool manufacturers have allocated considerable resources to the study of ergonomics and power hand tool use. Consequently, automotive manufacturers are searching for objective information relating power hand tool use to effects upon the operator. Because of their familiarity with the topic and magnitude of their concern, this workshop focussed upon tool use in the automotive manufacturing industry.

This project centered around the apparent need for more ergonomic research in the development, selection, and utilization of industrial power hand tools. Initial meetings with automotive representatives and tool experts indicated that they possessed information on the availability of tools. However, they lack extensive information on the operator interaction with specific tool mechanical properties. They need this information to understand and control potentially adverse biomechanical and physiological effects from power hand tools.

The consensus among representatives was a desire to see a more focused emphasis on tool design and operation. Therefore, the workshop attempted to address the following issues: (1) initiate a process of identifying specific concerns involving power hand tool design and use, (2) acknowledge what essential research and development has and has not been done, (3) coordinate activity to alleviate research and development redundancy, and (4) provide a focus for categorizing and prioritizing necessary research.

WORKSHOP ORGANIZATION

A workshop on ergonomic aspects of power hand tools in the automotive manufacturing industry was held on January 13 and 14, 1994, at NIOSH to address the issue of ergonomics and power hand tool design. The workshop was entitled "A Strategy for Industrial Power Hand Tool Ergonomic Research—Design, Selection, Installation, and Use Within the Automotive Manufacturing Industry." It consisted of a day and a half of panel discussions between representatives from the automotive manufacturing industry, the tool manufacturing industry, academia, government, and the consulting field. The workshop addressed the following issues:

- Areas of concern involving power hand tool design and usage
- Research and development
- Elimination of research and development redundancy
- Necessary research priorities

On the first day, the workshop was separated into three concurrent sessions for focused discussions: (1) epidemiology, (2) problem source identification, and (3) engineering controls/design/manufacturing. Before the workshop, panel members received a draft of Dr. Robert Radwin's paper entitled *Industrial Power Hand Tool Ergonomic Research: Current Research, Practice, and Needs.* This paper, which is a substantial attachment to this report, discusses these issues:

- Workers at risk
- Jobs and tasks with power hand tool usage
- Tools used for the job
- Biomechanical and physiological concerns
- Body segments affected
- Available industry specific injury rates
- Tool mechanical parameters, operational characteristics, and ambient conditions contributing to musculoskeletal stress
- Control technology available for preventing or controlling musculoskeletal stress
- Tool design, component design, fastening technology, and manufacturing methodology and testing as they pertain to biomechanical and physiological stress

Panel members discussed these and other topics of concern. The moderators, having input from panel members, provided a half-day summary of each session's discussions. The results of the discussion sessions were summarized and used for modifying and refining Dr. Radwin's paper. The final version is contained in these proceedings.

SESSION FINDINGS

The following section is a summary of the discussions that occurred in each session. Panel members were asked to provide comments and suggestions based on their activity and expertise in a particular area of work, research, and design.

Epidemiology

This session examined existing epidemiological research and discussed future research needs. The following concerns were highlighted during the discussion:

- Lack of epidemiological data relating hand tool use to specific workers or worker populations.

- Lack of good exposure/response data.

- Limited data on the relationship between power tools use and risk factors for WMSDs, including repetition, force, posture, vibration, contact stresses, etc.

The employee populations considered most often exposed to musculoskeletal stress associated with power hand tool use were the skilled workers, who constitute approximately 20% of the automotive industry work force. These workers may be involved in either nonstereotypic, nonrepetitive, or in repetitive work in structured jobs.

There was consensus on the need for more epidemiological data in the investigation of operator and power hand tool interaction. There was also consensus on a need for a better system of identification and integration of injury data and tool and job description data. An improved engineering data system containing, among other things, typical mechanical characteristics of the tool and material specifications would assist in identifying WMSD risk factors. Also, an improved epidemiological data system could assist in determining how to reduce risk in the following ways:

1. Evaluate exposure/response relationships between tool use and work-related musculoskeletal disorders.

2. Provide useful information for improving tool design.

3. Help optimize tool application (i.e., optimize tool choice).

4. Provide improved criteria for tool purchasing and acquisition.

The description of tool selection and use should include details of the tool operation (what the tool should be used for), workstation design, and other activities associated with the job. Epidemiological data should also include previous job information, such as particular job duration and time on job.

Problem Source Identification

This session discussed the extent to which current research knowledge identifies mechanical parameters, operational characteristics, and ambient conditions contributing to musculoskeletal stress. In this session, three interacting job design variables were identified as (1) worker, (2) tool, and (3) task attributes. Corresponding typical task risk factors were identified as static exertions, repetitive exertions, forceful exertions, contact stress, awkward postures, low temperatures, and vibration. In addition, mechanical risk factors related to tool design were considered to be load (mass), handle size, handle shape, handle orientation, feed force, torque, and vibration. Apparent research needs established during this session were:

1. Extensive literature search and analysis to highlight what is known and to identify research needs.

2. A strategy for optimizing interactions between worker, tool, and task attributes identified previously as dynamic interacting variables.

3. More emphasis on the entire job design with corresponding operational characteristics.

4. More dose/response data for a better understanding of tool-operator interaction and subsequent biomechanical and physiological reaction.

5. Fast, accurate, and practical methods for obtaining biomechanical, physiological, and psychophysical measurements.

6. Improved models of worker-tool-task interactions built on the realization that what has been considered acceptable may not be necessarily safe.

7. Better transfer of technological information among those involved in power hand tool research, design, test, usage, and procurement activities.

8. More epidemiological data, including theories and models.

Engineering Controls/Design/Manufacturing

The intent of this session was to discuss control technology necessary to prevent or control WMSD etiological factors. The discussions focused on current needs in the area of tool design, component design, fastener engineering, and manufacturing methodology and testing, taking into account biomechanical and physiological stress. The panel members agreed that there was a need for more research on WMSD risk factors, acute injuries, fastener technology, and tool testing. However, information gathering, access, and dissemination to support tool design, selection, and installation were the immediate needs. The following list consists of such information needs highlighted during this session:

1. The development of a systematic flowchart to understand the relationship among elements within the manufacturing process (computerized expert system).

2. The facilitation of more and improved communication among ergonomists, engineers, and designers for a more effective, systematic approach to the manufacturing process.

The lines of such communication could be augmented by the development of a better information translation and dissemination process. Some panel members and audience participants expressed a desire to have research information be more readily accessible to other researchers and individuals in the field. They also felt guidelines specific to industry should be established; however, these guidelines should focus on methodology and not on specific standards.

SUMMARY AND RECOMMENDATIONS

There was consensus across sessions that epidemiological research of power hand tools and operator interaction was needed. This need coincides with the apparent lack of epidemiological data pertaining to power hand tools, industrial operations, and rate of specific injuries. In each session, participants felt that more epidemiological information would augment other efforts in musculoskeletal stress identification and prevention. As an example, during the summary session it was indicated that more epidemiological data was needed to understand the magnitude of WMSDs. More worker characteristics and job specific data needs to be collected as epidemiological information to assist in obtaining an historical perspective and tracking workers on the job. Such epidemiological information should reveal power hand tool ergonomic research needs. However to adequately catalog research needs, an epidemiological procedure should include the identification of areas and criteria for tool research. The following example outline illustrates a conceivable procedure for the initial process of effective information gathering:

1. Identify power hand tools utilized in industry.

    - Identify tool specifications most often reported.

    - Define typical power sources.

    - Identify and categorize types of tools under development.

2. Identify problems associated with power hand tool use.

    - Highlight case studies and long-term epidemiological studies illustrating biomechanical and physiological effects of power hand tool use.

    - Categorize tool mechanical properties for ergonomic consideration. These properties may include

        — tool weight and load distribution,

        — tool grip size, shape, and texture,

        — torque reaction,

        — torque scatter performance, and

        — vibration

This categorization process should be flexible enough to allow for the inclusion of environmental and work technique interaction variables.

3. Identify research applicable to the area of adverse biomechanics and pathophysiology.

    - Who is performing the research?

    - What is their research concentration area?

    - Where is the research being done?

    - How is the research being done?

4. Determine areas in need of additional research.

   - Identify strategies for filling existing research gaps. This may require prioritizing research.

     — Determine if research gap(s) is worth filling.

     — Determine if current research can be extended to encompass power hand tool design topics not being investigated.

     — Determine necessary resources for accomplishing established goals.

   - Discuss possibility of coordinating research efforts between interested facilities:

     — Identify essential components for coordination.

     — Design the coordination process to allow for the variability and uniqueness in operation of each facility.

   - Assess needs for the development of medical surveillance programs to identify potential problem areas.

By providing a cohesive overall plan and coordinating the various parties, a mechanism avoiding duplication and promoting cooperation would be developed. This should lead to more efficient development of needed research or implementation of existing solutions.

Also based on session discussions and experiences summarized by participants during the workshop, there was a strong desire for improved communication and collaboration between the fields represented at the workshop. Although some research and design information may be available, workshop participants considered the lack of appropriate channels of communication to be a significant hindrance to adequate dissemination of sufficient information. A clearinghouse of such information would assist those involved in research and design, as well as individuals in the field, in seeking new, pertinent information. Panel members, and audience participants felt there was a substantial need for a forum or forums in which ideas, issues, and concerns could be objectively addressed.

STRATEGY PLAN

The establishment of a consortium including representatives from concerned parts of industry, academia, and government may well set the stage for discussion and possible cooperation for solving problems associated with WMSDs. The feasibility and creation of such a consortium is dependent on the cooperation of tool manufacturers, industrial tool users, and those involved in power hand tool research and testing. To elicit cooperation, those having access to specific resources must be willing to discuss a proposed strategy for action.

Conferences could be held at regular intervals with plenary papers, presenters, and specific workshops to improve communication and the transfer of applicable technological ideas. Also, during these conferences constant updating of information on the availability of specific research and intervention concepts could occur.

Potential Roles Within the Consortium

Several groups, including manufacturing companies, union-management safety and health joint groups, tool manufacturers, NIOSH, or others may have resources that could be applied to support this endeavor of cooperation. The allocation of such resources may include co-funding, or facilitating a conference or discussion session(s), and suggesting facilities available for research and development.

As an example, NIOSH can act as a partner for conferences while simultaneously being one of the major forces behind the development and support of a "clearinghouse" for information, translation, and dissemination. In taking this approach, NIOSH can provide the leadership and coordination that is necessary for initiation of such a strategy.

Although other funding and information sources may be needed, enough may be known already for this process to begin. The potential use of becoming involved with existing partnerships such as those offered by the University of Wisconsin-Madison Industrial Hand Tool and Ergonomics Research Consortium and the National Center for Manufacturing Sciences (NCMS) should be considered. These partnerships are examples of associations that may be addressing some of the current concerns and issues involving power hand tool ergonomic research.

The inability to transfer up-to-date, pertinent, power hand tool information to industry may indicate a core problem with the process of acquisition and dissemination of power hand tool ergonomic information. This does not entirely result from a lack of concern, or limited resources, but rather a lack of an appropriate vehicle for information acquisition and dissemination. Such a lack hampers the identification of problems and possible solutions even though potential solutions to particular problems or other established preventive strategies may be known. In addition, reported information may not be available in a form that is immediately usable by individual's seeking assistance with design, selection, installation, and/or use of power hand tools. Therefore, it is perhaps necessary to develop a system allowing individuals from various activity fields to communicate openly and exchange ideas and concepts in the prevention of musculoskeletal stress to the operator of power hand tools.

The creation of a central location for the objective, nonproprietary information gathered from government, industry, and academia would increase the accessibility for all those interested, and possibly decrease redundancy in research and engineering. A central location or "clearinghouse" would serve as a vehicle for those seeking pertinent data and assistance in dealing with concerns and issues concentrated on power hand tool ergonomics. This concept of a "clearinghouse" could also include, if necessary, a process for digesting information and disseminating it in a user friendly form for ready access.

REFERENCE

BLS (1993). Occupational injuries and illnesses in the United States by industry, 1991-92. Washington, D.C.: U.S. Department of Labor, Bureau of Labor Statistics.

Industrial Power Hand Tool Ergonomics Research

Current Research, Practice, and Needs

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1 INTRODUCTION

Scope of the Problem

There is a crucial need for research concerning power hand tool design, selection, installation and use, and the consequences of power hand tools for operators. The high incidence of musculoskeletal injuries in manufacturing has prompted concern that workers be protected from excess physical stress arising from exposure to repeated and sustained motions and exertions, work requiring awkward postures, contact stress, cold, and vibration. Both management and labor have come to recognize that because of the widespread use of power hand tools, improvements in the interface between the human operator and the tools frequently employed for repetitive manual work can affect a large number of jobs. Consequently, power hand tool manufacturers are being challenged by customer demands for products that help minimize physical stress. The lack of specific information has prompted industry to call on ergonomics researchers to provide knowledge about the complex relationships between physical stress and power hand tool operation, which can be applied to prevent musculoskeletal stress disorders.

Background of Injuries Associated with Power Hand Tool Use

At the end of the nineteenth century an American inventor named MacCoy developed an implement called a pneumatic tool, powered by compressed air and designed to be held in the hands (50 and 100 years . . . . 1989). It did not take long until these tools were used for rock breaking and demolition. By 1918 Hamilton, studying Indiana stonecutters who worked extensively with air hammers, concluded that the combination of vibration, cold temperatures, and the manner in which the tools were held and used were responsible for numerous symptoms, including numbness, vasospasms, and manual dexterity deficits (Hamilton 1918). Air-powered tools were limited to chipping and stone cutting.

The assembly line brought highly specialized and repetitive work into the factories. Rather than using a variety of tools for completing an entire project, a worker used a relatively small number of tools to repeatedly accomplish a specific task. In fitting with this task procedure, power tool use has become widespread in manufacturing. Furthermore, workers who use power hand tools often spend a large portion of the workday holding and operating them.

There have been numerous reports of injuries and disorders associated with jobs involving use of power hand tools. Some disorders associated with power hand tool use include

- acute musculoskeletal injuries,

- muscle, tendon or ligament tear, bone fractures, etc.,
- chronic musculoskeletal disorders,
- cumulative trauma disorders,
- vascular disorders,
- vibration white finger,
- hearing impairments, and
- respiratory disorders

A survey of state and federal agencies found that hand tool use was associated with 9% of all work-related compensable injuries (Aghazadeh and Mital 1987). The majority of workers were injured when they were struck by or were struck against hand tools, or when they overexerted themselves (Mital and Kilbom 1992). Power hand tool vibration exposure has been associated with vascular disorders and neuromuscular disturbances (NIOSH 1989). Vibration has also been cited as an etiologic factor of chronic nerve and tendon disorders, including carpal tunnel syndrome and tendinitis (NIOSH 1989). Jobs involving highly repetitive hand tool use have been associated with physical stress factors for musculoskeletal disorders (Cannon et al. 1981; Rothfliesch and Sherman 1978; Silverstein et al. 1987). A surveillance study by NIOSH found that musculoskeletal injuries accounted for 24% of all hand tool injuries (power and non-power hand tools) reported in the Supplementary Data System (SDS) (Myers and Trent 1988). These injuries included disorders of the soft tissues, such as the tendons, nerves, muscles, and connective tissues. The same study found that for operations involving power hand tools, inflamed wrist joints were more common than wrist lacerations and other acute injuries.

Power Hand Tools Used in Manufacturing

Power hand tools in manufacturing include portable power hand tools generally used throughout industry for fabricating, assembling and disassembling, and forming material. Portable power hand tools used in manufacturing are listed in Table 1.

2 POWER HAND TOOL ERGONOMIC TOPICS

This section addresses ergonomic research in the identification of mechanical parameters, operational characteristics, and ambient conditions that contribute to musculoskeletal stress for the operator.

Table 1. Manufacturing power hand tool categories and examples

Type of power tool	Examples
Thread fastener driving tools	Screwdrivers and nutrunners (pistol grip, angle, in-line) Impact wrenches Ratchet wrenches Tube nut wrenches
Abrasive material displacement tools	Sanders (rotary, orbital, belt, drum, disc, oscillating, etc.) Grinders (angle, die or straight, horizontal, vertical) Buffers Polishers Reciprocating and rotary files Wire brush tools
Portable cutting tools	Reciprocating saws Panel saws Trim saws Shears and nibblers
Hole preparation tools	Drills (angle, in-line, pistol grip) Reamers Tapers
Linear motion securing tools	Staplers Hog ringers and clinchers Pressed-in or driven insert fastener tools Nail drivers Pin drivers
Percussion tools	Riveting tools Chipping hammers Scalers Engraving tools
Special purpose tools	Cable binding tools Clip squeezers Electrode dressers Lint or roll pickers Multiple spindle tools Tab set tools Tube rollers Wire wrapping and unwrapping tools Wire strapping tools

Problems Associated with Power Hand Tool Use

Power hand tool operation has been associated with exposure to a variety of physical stress factors. The relative contribution of physical stress factors associated with work involving hand tools has been difficult to separate from power hand tool use because many manufacturing jobs involving power hand tools also involve extensive use of the upper limbs. For instance, power hand tool operators may need to assume awkward postures dictated by a specific tool handle location and/or work piece orientation. The same tool may be used repetitively for short-cycle time tasks. Some power tools can also introduce vibration and have triggers that may cause contact stress from sharp edges against the fingers or palm. The hands may at the same time be exposed to cold air produced from pneumatic tool exhaust outlets.

Physical Stressors

Physical stressors associated with hand tool operation include awkward postures, forceful exertions, repetitive motion, contact stress, and vibration. The level of physical stress associated with chronic work-related musculoskeletal disorders may be so small in magnitude that any single occurrence seems harmless, but repeated exposure over several weeks, months, or even years may lead to an illness. The objective when selecting, installing, and using power hand tools is to minimize operator exposure to each physical stress factor. All of these physical stress factors need to be considered in relation to one another, because reducing exposure to one factor, may have the adverse effect of increasing exposure to another factor.

Posture refers to the position that the body assumes for a specific task. While it is not possible, or even desirable, to immobilize the body in one "ideal posture," some postures are more stressful than others and should be avoided. Handling a power tool while flexing or extending the wrist and rotating the forearm may irritate tendon attachments at the epicondyle. An example is provided by arm position during operation of a right angle nutrunner where the wrist is flexed while the forearm is pronated. An extended wrist and supinated forearm operating a pistol-grip drill on the underside of a horizontal surface at eye level is another example. Posture is affected by work location, work position, tool shape, and worker size.

The *force* requirements for a job are often related to the weight of the tools being handled. The distribution of tool weight can also affect how force is transmitted to the user. Force demands that exceed an operator's strength capabilities may cause loss of control, leading to an unintentional injury and poor work quality.

Repetitiveness refers to the number of times that similar movements are repeated over time, or how often certain exertions are made. Repetitive operations often require repeatedly making the same movements and exertions over again. The risk of developing a hand or wrist disorder is significantly increased for workers performing highly repetitive and forceful exertions (Silverstein et al. 1987).

Contact stresses are produced when parts of the body come into contact with objects, resulting in forces transmitted through the skin to underlying structures, such as muscles, tendons and nerves. Some areas of the body are better suited for bearing contact stress than others. The skin on the back of the hand, for example, is much thinner than the palmar side and less suited for withstanding loads. Contact stresses are related to the force and area of contact, described by the pressure exerted against the skin. Pressure is the force exerted over a given area, which increases when contact area decreases. Therefore a repeated force or load over a small surface area of the palm may result in pain and detrimental stress to the hand.

Symptoms in the arm and hand associated with prolonged and repeated vibration exposure are collectively referred to as *hand and arm vibration syndrome.* These include vascular disorders, joint deformations, soft tissue damage, and neurological disturbances (Hasan 1970). Vibration white finger, is a vascular disorder, resulting in episodic vasospasms in the fingers of occupational origin, causing them to appear white when exposed to a cold environment. Vibration has also been cited as a factor in chronic nerve disorders, such as carpal tunnel syndrome (Armstrong et al. 1987; Cannon et al. 1981; Rothfliesch and Sherman 1978).

Other risk factors for work-related musculoskeletal disorders can adversely affect vibration transfer to the tool operator's hand. Highly repetitive work, for instance can affect vibration exposure through accumulated doses of repeated vibration exposure. Also, repetitive operations increase vibration exposure time, and forceful exertions, which improve coupling between the handle and hand, increase vibration transmission. Work standards are additional factors affecting the work environment in which hand tools are used. One study found the prevalence of vibration syndrome was greater among incentive workers than among hourly workers (Wasserman et al. 1981). The report suggested that the intensity of incentive work increased grip exertions and improved coupling between the hand and the power tool, thus resulting in increased vibration transmission. A direct relationship was observed between repetitiveness and vibration exposure (Radwin and Armstrong 1985). Workers exposed to greater repetitive stresses were also subject to greater exposures of vibration.

Fingers and hands can be exposed to cold when work is in a cold environment, or when air blows across the hands, arms, or face from pneumatic power tools exhaust vents. Handles made of conductive materials can conduct heat away from the hands, particularly when the tool is used in cold environments or when air passes through the pneumatic hand tool handles. Cold hands can affect strength, manual dexterity, and tactual sensitivity. Allowances should be made for those effects when power tools are selected for use in cold work environments.

Tool Selection

Tool selection should be made within the context of the specific job. By considering the ergonomic aspect of tool application for a specific job, the adverse effects of using the wrong tool can be prevented. It is generally agreed that physical stress, fatigue, and WMSD can be prevented or reduced by selecting the proper tool for the task. Usually tools regarded as best for the job are the ones that minimize physical stress by producing low demands of force on the hand; that are not awkward to hold and handle; and that minimize shock, recoil, and vibration. Physical stress on the tool operator is often considered as a result of *how* a particular tool is used for a specific task, rather than just its use. Therefore, properly using the correct tool for the task should also be considered in the context of tool selection.

Currently, there are tools being marketed as "ergonomic." Many of these tools have features that may have ergonomic benefits when used correctly. Although some of these tools may have desirable properties, ergonomics experts concur that selecting a specific tool without considering the task requirements, work station design, and setup may not prevent adverse effects, and in some cases can have potentially detrimental consequences. Ergonomic principles, along with tool design, should therefore guide the selection, installation, and use of the right tool for the right application.

Hand tools should be selected based on physical process engineering requirements and ergonomic criteria. When both of these aspects are considered, the appropriate hand tool for a particular job should:

- Maximize work performance.
- Enhance work quality.
- Minimize operator stress.
- Prevent fatigue onset.

Engineers often specify power hand tool requirements for a specific job in terms of the manufacturing process, such as the drill bit speed needed to make a specific hole in a material, or the torque needed to tighten a screw for a threaded fastener joint. Although these specifications affect the quality and performance of the physical process, they often fail to take into account the physical capabilities of the hand tool operator performing the work. If not considered, improper use of certain power hand tools may lead to operator fatigue or to increased risk of musculoskeletal injury.

The physical process task requirements and the capabilities of the tool operator often interact. If the task requirement exceeds an operator's capabilities, task performance can be compromised. If an operator becomes fatigued, work performance and quality will suffer. Power hand tool selection for a particular task should be based on (1) process engineering requirements, (2) human operator capabilities, and (3) workstation and task factors.

Process Engineering Requirements

Power hand tool selection first involves finding a specific tool capable of performing the physical task. For instance, if the operation involves tightening a screw in an assembly task, process engineering requirements undoubtedly include choosing a tool capable of producing a specific torque, rotating the spindle at a particular speed, and having the correct spindle and socket size. These manufacturing process requirements are often based on the product design and parameters needed for accomplishing the task quickly and reliably, at the desired quality level. Process engineering requirements for hand tools may include specifications for the following:

- Speed (rpm)
- Dimensions (cm)
- Torque (Nm)
- Feed force (N)
- Power (W)
- Weight (N)
- Activation (trigger, push-to-start)
- Spindle and chuck diameter (cm)
- Noise Level (dBA)

- Air pressure (kPa)
- Precision and tolerance (mm)
- Bits, blades, and abrasives
- Power source (air, electric, hydraulic)

Human Operator Capabilities

Another important consideration in hand tool selection is how these engineering requirements will affect the tool operator at the "operator end" of the tool. For example, a power hand drill operation requiring a certain diameter hole drilled in a specific material may require a minimum feed force (the amount of force needed for the drill bit to work against the material). This force requirement at the drill bit directly affects the hand tool operator's exertion because the operator must apply force against the handle to push the drill against the work material. Furthermore, the type of exertion may be different if the drill has a pistol-grip handle, rather than an in-line handle.

The feed force necessary for accomplishing a task is only one type of force affecting the operator. Power hand tools also *generate* forces, which in turn can act against the operator. For instance, the torque at a power screwdriver spindle results in a reaction force at the tool handle. The human operator must react against this force by exerting an equal and opposite force to hold onto the tool handle as the tool functions. The amount of force generated and the manner in which that force is directed back to the operator is influenced by the power hand tool capacity, its dimensions, and the handle shape. Additional force demands on the operator's hands may be introduced due to the posture an operator must adopt while holding the tool and the manner in which he/she must grip the tool.

Furthermore, the posture assumed when a particular tool is held for a task can affect the operator's ability to use that tool by affecting his/her strength capabilities. The handle size and shape can also limit an operator's ability to produce forces. Gloves can further affect the force available for gripping handles. Understanding and controlling these ergonomic factors are important for limiting physical stress to the tool user and for producing optimum work performance.

Typically, power hand tools utilize an auxiliary power source external from the human body. Common power sources include pneumatic or air pressure, electric current, hydraulic pressure, gasoline motors, or a power explosion. The output from power hand tools is often many times greater than what can be produced by a bare hand, even if manual hand tools were used. The hand, however, must react against the increased forces and torque produced by power hand tools. Since the energy provided from power hand tools is normally greater than the energy produced manually, the potential for injuries is greater. These forces can be reduced through the mechanical advantage provided by handles and external suspension systems.

When selecting a hand tool, the following hand tool operator characteristics should be considered:

- Strength
- Anthropometry
- Manual dexterity and motor capabilities

Strength

Safe power tool operation requires that an operator possess the ability to adequately support the tool in a particular position, while reacting against forces produced by the power tool. The capacity to produce forces is usually referred to as *strength*. Strength is therefore the maximum force an individual can produce. The ability for hand tool operators to produce the required forces should be taken into account when hand tools are selected. An operator normally cannot use a tool for long without becoming fatigued if required to exert force at maximum capacity.

The ratio of the required force to an individual's strength approaches unity as the force requirement approaches an operator's strength capability. This proportion is related to the ability to sustain a given exertion, and to the onset of localized muscle fatigue. The greater the proportion of strength that a repeated exertion requires, the quicker the operator will be unable to sustain that exertion, and the more rapid the onset of fatigue. Tools should therefore be selected so that this proportion is minimized. This can be accomplished either by selecting tools requiring less force or by using tools in ways that maximize an operator's strength.

Strength is affected by body position, the direction of exerted force relative to the body, the type of grip used for holding the tool, and the handle size. Operator strength capabilities change as the position of limbs and body changes. For instance, arm muscles are strongest when pushing and pulling in a direction towards and away from the body (i.e., push and pull), as opposed to moving across the front of the body (i.e., left and right) (Greenberg and Chaffin 1977).

Grip strength depends on the type of grip used for holding a handle. The hand is less capable of performing precise movements and exertions when using a power grip because of the large muscles recruited. It is the large muscles that provide the high strength in power gripping.

Handle shape can affect hand and arm strength (Fothergill et al. 1992). Handle size affects grip strength. If an object is too large or too small, the strength of the hand is greatly compromised. Numerous studies have demonstrated the effects of handle size on grip strength. When these data guide the selection of tool handles, it is important to know not only the handle span and handle circumference the data represent, but also the handle shape.

A particular finger, or combination of fingers, can also affect grip strength (Radwin et al. 1992). The thumb, index, and middle fingers are the strongest fingers and should be utilized for producing the most grip force. The ring finger and small finger are less capable of producing forces and should be primarily used for stabilizing handles.

Some pistol-grip power tool designs permit the thumb and index to assume a precision grip, but also provide a handle for reacting against spindle torque. Tools designed for one type of grip may sometimes be used in a different manner. Handle dimensions should differ, depending on whether they are being used for precision tasks, power manipulations, or for carrying.

Increasing the surface area of contact between the handle and the hand increases the amount of torque that can be generated. Grip strength, however, has been shown to decrease when handles with diameters greater than 50 mm are used (Pheasant and O'Neill 1975).

Anthropometry

The population of workers that will use the tools is another important consideration. Strength decreases for aging populations (Fraser 1980). Hand size and strength are related to gender.

Worker anthropometry can affect the posture a worker assumes when operating a hand tool. The ideal work location for tall workers may be too high for short workers. The location, orientation, and tool design should all be considered together along with the stature of the worker (Armstrong 1986a; Armstrong et al. 1986b). In situations where the work location and orientation cannot be adjusted to suit the worker, it may be possible to select another tool. In cases where the work specifications determine the tool design, it may be possible to change the location or orientation of the work.

Manual Dexterity and Motor Capabilities

There is a tradeoff between the increased mechanical advantage provided by a long tool, versus its weight and size, and the ability for an operator to manipulate and handle it (Sperling et al. 1991). A tool that is too large may be too difficult to use for performance of precision work. Operations that require low force and precise movements may require a tool handle that permits precision gripping and pinching to maximize the fine motor control capabilities of small muscles in the hands and arms. The type of grip suitable for a manual tool operation is often limited by the size of the tool. Although a power grip can provide greater strength than a pinch grip, a pinch grip provides greater control of precision movements. Consequently, tool selection should optimize the proportion of strength that an operator must exert with the ability to make necessary movements with speed and precision. One method used for muscle driven tools involves time, force, and precision considerations (Sperling et al. 1993).

Workstation and Task Factors

Power hand tool characteristics and operational requirements for hand tools may include:

- Tool weight and load distribution
- Triggers
- Feed and reaction force
- Handles
- Work location and orientation
- Tool accessories
- Vibration
- Noise

Tool Weight and Load Distribution

Musculoskeletal injuries may arise simply from the act of lifting and manipulating power hand tools if they are too heavy or if manipulation involves awkward postures (Myers and Trent 1988). The actual time workers spend operating power hand tools on automobile assembly lines is only a small portion of the overall cycle time, and the majority of the time is spent handling and manipulating power hand tools (VanBergeijk

1987). One study found that the frequency of plant medical visits were significantly related to the mass of the tools operated (Schlegel and Willcoxon 1989).

An operator's exertions can be affected by the specific type of external power. A large electric motor, for instance, may carry more weight than a comparable air-powered tool. External power accompanies additional ergonomic considerations. These include the added weight from having a motor, handles for supporting power tools, triggers for activation, a feed and reaction torque, use of balancers, torque reaction bars and other accessories, a required posture, vibration, and acoustical noise. Also the required use of tool accessories such as air hoses, power lines, couplings, and adapters contribute an often overlooked addition of weight that the tool operator must hold and carry.

Psychophysical experiments have provided some insight into the load that power tool operators prefer using. When experienced hand tool operators were asked to rate the mass of the power tools they operated on continuous scales between 0 to 10, tools weighing 0.9 to 1.75 kg mass were rated "just right" (Armstrong et al. 1989). Another psychophysical experiment showed that perceived exertion for a tool mass of 1 kg was significantly less when compared to tools with masses of 2 kg and 3 kg (Ulin and Armstrong 1992b). A study investigating muscle activity of the hands and forearms observed a significant correlation between tool mass and grip exertions (Grant et al. 1992).

There can be a tradeoff between the selection of a lightweight tool and the benefit of the added weight for performing operations that require high feed force. For example, the power available for a grinding task increases with the increasing mass of a grinder. Reducing the weight of a grinder may increase the amount of feed force and time necessary for the operator to accomplish the task, consequently, also increasing an operator's exposure time to other variables such as vibration.

Triggers

Triggers extending far away from the handle make it necessary to use the distal finger segments. This has been associated with a stenosing tenosynovitis of the volar finger tendons. Use of the distal phalanx to actuate a tool trigger contributes to trigger finger (Tichauer 1977). Trigger finger derives its name from the snapping sensations and movements resulting from stenosis of the tendon sheaths.

Throttle force is the force needed to overcome the resistance of a valve, or to close an electrical switch when a power hand tool is activated. Standards developed by the American National Standards Institute (ANSI) specify that a tool should shutoff when the trigger is released, often making a spring mechanism necessary (ANSI 1975). The spring action also means that the fingers must work against a spring force, in addition to working against the force needed to activate the tool. Some tools allow for multiple finger activation to distribute load among fingers (Oh and Radwin 1993). However, when precise trigger control is necessary, such as in variable speed tools, four finger control is not feasible due to the necessary stabilization of the tool handle from other fingers.

Feed and Reaction Force

High feed forces are associated with power tool operation requiring sustained exertions, such as drills. Power screwdriver feed force may be affected by the fastener head used (Cederqvist and Lindberg 1993). The type of fastener head and its orientation affect the amount of force and posture the operator must assume to accomplish the task. Self-tapping screws require more force than pre-tapped holes. Feed force requirements increase as torque level increases for cross recess screws. Material hardness is also a feed force factor for self-tapping screws.

Nutrunners account for almost 75% of the power hand tool inventory of a typical automobile assembly plant, of which there may be as many as 4,500 tools (VanBergeijk 1987). Nutrunner torque output can range from less than 0.8 Nm to more than 700 Nm. Forces acting on the hand when operating a nutrunner is operated include (1) push or feed force, (2) tool support or holding force, and (3) torque reaction force. Feed force is necessary for starting a fastener and keeping the bit or socket engaged during the securing cycle, and it is affected by the work material and design of the fastener. Holding force is the force necessary for supporting a nutrunner, and it is dependent on the tool mass, its center of gravity, the length of the tool, and possible air hose attachments. Reaction torque is produced by spindle rotation and is affected primarily by the spindle torque output and tool length.

As torque is applied to a threaded fastener, it rotates at a relatively low spindle torque until the clamped pieces come into intimate contact. This torque can approach zero when free running nuts are used, or it can be significant when locking nuts, thread interference bolts, or thread forming type fasteners are used. This is called the run-down phase. After the fastener brings the clamped members of the joint into initial, intimate contact it continues to draw the parts together until they form a solid joint. When the joint becomes solid, continued turning of the nut results in a proportionally increasing torque. This is the elastic portion of the cycle and is the time when reaction torque forces are produced. Torque build-up, and consequently torque reaction force, continues rising at a fixed rate until peak torque is achieved, which is the clamping force of the joint. These forces require a reaction from the operator to control the tool and keep it stable.

Forearm flexor muscle activity, measured by root-mean-square electromyography (RMS-EMG) while operating an automatic air shutoff right-angle nutrunner during the torque-reaction phase, was more than four times the muscle activity used for holding the tool, and two times the run-down phase (Radwin et al. 1989). Forearm flexor EMG activity during the torque-reaction phase increased for tools having increasing peak spindle torque.

Threaded fastener joint stiffness ranges from hard to soft. Hard joints are formed when two solid and fairly rigid objects are brought together, such as when a pulley is attached to a crankshaft. Soft joints involve objects having more elastic properties, such as when a body mount is attached. Torque Rate is used for quantifying joint stiffness and is defined as the angular rate of torque build-up to the resistance of tightening. A high torque rate joint is defined by the International Standards Organization (ISO) as one where the torque increases from 50% to 100% of the peak torque in less than 30° of angular displacement. A low torque rate joint increases from 50% to 100% of peak torque in more than 360° displacement (ISO 1981).

The tightening process for high torque rate joints is extremely fast. Reaction forces transmitted to the tool operator peak in a very short time, determined by the time necessary to reach the installed torque level and the delay of the tool torque control mechanism. The actual relationship between installed torque and the reaction torque is affected by the mass of the tool, the size of the operator, and the way the tool is held by the operator. The reaction torque and, consequently, the reaction force can be greater or less than the target torque (ISO 1981). One study showed that muscle response was affected by torque build-up time (Radwin et al. 1989). Average EMG activity was greater for 0.5 s torque build-up time than for a 2 s torque build-up time for right-angle nutrunners, ranging in torque between 30 Nm and 100 Nm.

There is a tradeoff for high torque/high feed force tools when posture is used as one of the criteria for tool selection. Although an in-line power tool maintains a neutral wrist posture when working on a horizontal surface, high torque in-line screwdrivers require high grip force. Consequently, less force may be needed for a pistol-grip tool than for an in-line tool. Use of a pistol-grip power tool, however, requires relocation of or reorientation of the work so that a stressful wrist posture is not assumed.

The three major operating modes for nutrunners are (1) mechanical clutch, (2) stall, or (3) automatic shutoff. Although clutch tools limit reaction torque, ratcheting clutch tools can expose workers to significant levels of vibration if used frequently. When a stall tool is used, maximum reaction torque time is directly under operator control by a release of the throttle, which can last as long as several seconds. Stall tools tend to expose an operator the longest to reaction torque. The speed of the shutoff mechanism controls exposure to peak reaction force for automatic shutoff tools. Consequently, automatic shutoff tools have the shortest torque reaction time since these tools cease operation immediately after the desired peak torque is achieved. One study found ground reaction forces were smallest for operators running right-angle nutrunners having fast torque shutoff mechanisms, and handle displacement was greatest when delayed shutoff mechanisms were used (Kihlberg et al. 1993). Another study found that perceived exertion ratings increased as torque impulse increased (Freivalds and Eklund 1991).

Handles

Power tool handles are often categorized as in-line, pistol-grip, angle, and accessory handles. The particular handle shape selected depends on the magnitude of reaction torque, the location and orientation of the work, the location of the operator, and the accessibility of the work. When experienced tool operators were asked to rate power tool handle size on continuous scales between 0 to 10, all tools having handle circumferences less than 12 cm were rated "just right." When provided with a simulated power tool having a continuously adjustable handle span, the preferred handle size increased as hand size increased, suggesting that tool handles available in different sizes are preferred over one-size handles. When pistol-grip nutrunner operators were allowed to adjust the handle span to any size they preferred, handle size increased proportionally to hand length (Oh and Radwin 1993).

The shape of the tool handle can affect the mechanical advantage that the operator has for reacting against tool forces. A nonspherical handle can provide an improved reaction arm for in-line power tools. The most common nutrunner configurations are in-line (straight), pistol grip, and right angle. Right-angle nutrunner operation often requires use of both hands, especially when larger tools are operated, however, only one hand usually is affected by reaction torque. The hand holding the distal handle is used for reacting against the torque reaction force and providing tool support, while the other hand produces push force.

Work Location and Orientation

A series of psychophysical studies examined perceived exertion and postural discomfort during power hand tool operation (Ulin et al. 1992a; Ulin et al. 1993a; Ulin et al. 1993b). Subjects were asked to drive screws using small (3.2 Nm) power screwdrivers under various workstation conditions, and then were asked to rate perceived exertion using Borg's 10 point scale. When working on a horizontal surface, the operators' perceived exertion levels increased as horizontal distance increased. The most comfortable vertical location for tool use was between 102 and 153 cm. The most comfortable horizontal location for using tools was within 38 cm of the worker. Driving screws at a 114 cm vertical work location had the minimum perceived exertions for right-angle, pistol-grip, and in-line tools. When the screws were driven on a vertical surface, the minimum perceived rating for the pistol-grip tool occurred for 114 cm and 140 cm, and the lowest ratings for the in-line and right-angle tools occurred for 191 cm. When a horizontal work surface was mid-chest or elbow height, right-angle and in-line tools received the best ratings, but the pistol-grip tool received the best ratings for screws driven near mid-thigh height.

The above mentioned psychophysical studies agreed with mannequin predictions, which indicated an optimal workstation height for these power hand tools between 100 cm for a fifth percentile female and 121 cm for a ninety-fifth percentile male (Armstrong et al. 1986b). A survey of power hand tool operators also had similar results (Armstrong et al. 1989). Operators rated vertical heights between 102 cm and 153 cm, and horizontal distances within 38 cm as the most comfortable.

Tool Accessories: Balancers, Articulating Arms, and Other Accessories

Spring or air balancers are available for counterbalancing tool loads in the hands. Articulating arms and hoists will reduce the weight of heavy power tools. Special attention may be required to install balancers so that minimal effort is needed when holding and using the tools in the desired work location. Spring counterbalances produce a force that opposes gravitational forces so the tool weight is reduced. If these balancers are not installed correctly, however, they can actually have the reverse effect of increasing the opposing force necessary to keep the tool in place.

Vibration

Vibration is an intrinsic property of power hand tool operation and can be a by-product of its operation, or it may be the desired action. Vibration levels depend upon hand tool size, weight, method of propulsion, and the tool drive mechanism. Continuous vibration is inherent in reciprocating and rotary power tools. Impulsive vibration is produced by tools operating by shock and impact action, such as impact wrenches or chippers. The tool power source, such as air, electric, or hydraulic, can also affect vibration. Vibration is also generated at the tool-material interface by cutting, grinding, drilling, or other such actions. The parameters of the generated vibration can be affected by work material properties, disk abrasives, abrasive surface area, and fastener type.

Accessory attachments may become a source of vibration if they fit improperly or cause a tool to become unbalanced. An example is a loosely fitting extension shaft on a nutrunner, which causes a tool usually not considered a vibrating hand tool to produce considerable vibration from the wobbling action of the rotating spindle. Tools requiring maintenance or those becoming unbalanced are also potential sources of vibration. Some tools are specifically designed to minimize vibration and may be fitted with isolation attachments.

Handle location and the type of tool can have a dramatic effect on the level of vibration transmitted to the operator. Vibration measurements made from a large chipping hammer running at full throttle indicated the acceleration ratio between the chisel end and the rear handle was approximately 78:1 (Wasserman et al. 1981). The same study also found rear handle acceleration levels for a small stone chipper were as high as 2.5:1, apparently because of very little mass damping for this light weight tool.

Vibration may affect the force exerted in repetitive manual tasks. Hand tool vibration can introduce disturbances in neuromuscular force control resulting in excessive grip exertions when an operator holds a vibrating handle (Radwin et al. 1987). A study on pneumatic hammer recoil observed a stretch reflex and muscular contractions in the elbow and wrist flexors (Carlsöö and Mayr 1974). Since forceful exertions are a commonly cited factor of chronic muscle, tendon, and nerve disorders of the upper extremities, vibrating hand tool operation may increase the risk of work-related musculoskeletal disorders through increased grip force. The results of Carlsöö and Mayr's study demonstrated that grip exertions increased with tool vibration. The magnitude of this increase in grip force was similar to the increase in grip force for a two-fold increase in load weight.

Vibration has been shown to produce short-term sensory impairments (Radwin et al. 1990a; Streeter 1970). Recovery time is exponential and can require more than 20 minutes (Kume et al. 1984). Tasks requiring a high degree of tactile sensitivity, such as inspecting for smoothness or rough edges, should avoid the involvement of tools producing vibration in the 160 Hz range since sensory performance, and thus work performance in manual inspection task will be affected. Sanding and grinding operations are two examples of tasks requiring inspection for smoothness. Workers often sand or grind a surface and periodically inspect their work using tactile inspection to determine if the surface was sanded to the desired level of smoothness. Diminished tactility may result in a surface feeling smoother than it is, while actually being rougher surface than desired.

Unbalanced grinding wheels can generate periodic forces at a frequency equal to the rotational speed and at multiples of this frequency. Usually the frequency of the rotational speed dominates over the higher frequency vibration. When grinding wheel imbalance causes vibration, there is little to be gained by a machine that produces less vibration. The best method of reducing this type of vibration is by elimination of the imbalance and by isolation of the operator. Increasing the tool moment of inertia makes the handle less sensitive to unbalanced wheels. This is accomplished by distributing the tool mass as far from the center of gravity as possible. Moving the center of gravity as close to the grinding wheel as possible will decrease the wobbling motion. Oftentimes impulse tools are considered because they can produce high torque levels without producing high reaction forces. The tradeoff is low reaction torque for increased vibration.

Noise

Loud noises can be produced by power hand tool motors and from vibration of moving objects, such as a grinding wheel against a grinding surface. Pneumatic vane motors generate sound when a major change in airflow occurs due to pressure differences and compression of air when the vanes rotate. The sound has a fundamental frequency equivalent to the motor rotation speed times the number of vanes. Vibration in the tool housing can also transmit noise to the surrounding air.

Airflow noise is another common source of noise. This is caused by the formation of turbulence inside the tool. If air passes sharp corners or edges, airflow noise is enhanced. The dominant source of the airflow noise is strongly dependent on the speed of air leaving the housing of the tool.

The Relationship Between Tool Mechanical Properties and Musculoskeletal Stress

Power hand tools, in conjunction with the specific work and environment in which they are used, can potentially introduce factors that are associated with musculoskeletal stress. Some of these potential conditions are summarized in Table 2. Physical stress factors may be reduced or eliminated by changing the tool, task, or work environment. Stress factor reduction involves identifying properties of the specific power hand tool needed for a task.

Specific power hand tools can introduce varying levels of musculoskeletal stresses, depending on certain properties of those tools. For example, the force needed for carrying and positioning a power hand tool often depends on the tool load. Consequently a heavy tool requires greater exertions than a less heavy tool. Although an exertion of less force is the desired outcome, for certain tasks a heavy tool is more advantageous for the operator than a lighter one. There are several parameters associated with specific power tools that affect these mechanical properties. Tool load is affected by tool mass, mass distribution, use of an external support mechanism, and

Table 2. Some physical stress factors associated with common power hand tool use

Specific tool	Potentially stressful tool condition	Resulting operator stress factors
Nutrunner	Operating a high torque nutrunner without use of a reaction arm or other support	Forceful exertions
	Securing many screws in a short work cycle	Repetitive motion Repetitive exertions
	Operating tool in improper location for the tool shape or handle orientation	Awkward postures Forced exertions
	Operating tool with a stall torque control mechanism	Sustain exertions
	Carrying and positioning heavy weight tools	Sustain exertions
	Exerting high feed force	Contact stress Sustain exertions
	Blowing air exhaust towards operator's hands and arms	Exposure to cold temperatures
	Ratcheting clutch torque control mechanism	Vibration exposures
	Rattling long extension when spindle rotates	Vibration exposures
Grinders	Rotating grinding wheel unbalanced	Forceful exertions
	Grinding wheel abrasive contacting work material	Repetitive motion Repetitive exertions
	Operating grinder in improper location for tool shape or handle	Awkward postures Force exertions

(Continued)

Table 2 (Continued). Some physical stress factors associated with common power hand tool use

Specific tool	Potentially stressful tool condition	Resulting operator stress factors
	Using inadequate handle size	Sustain exertions
	Using too fine or worn grinding wheel	Sustain exertions
	Grinding wheel catching on work material	Contact stress
	Producing dust while grinding	Exposure to cold temperatures
Drills	Needing feed force for hard work material	Sustain exertions Contact stress
	Using worn out drill bit	Sustain exertions
	Using inadequate size handles	Sustain exertions
Staplers hog ringers	Having shock and recoil	Vibration exposures
	Operating tool in improper location for tool shape or handle	Akward posture
Chippers	Having impulsive reaction forces	Vibration exposure
	Handling heavy chipping hammer	Forceful exertions
Riveters & bucking bars	Having shock and recoil	Vibration exposure
Impact wrenches	Using a power tool containing a hammering drive mechanism	Vibration exposure
Power tool accesories	Improperly setting counterbalance	Vibration exposure Noise exposure

the manner in which the power line or air line is attached. Some mechanical tool properties and tool-related parameters affecting these properties are listed in Table 3. Engineering control strategies often make use of these properties for mitigating potentially stressful conditions. Mitigation of potentially stressful conditions can often be accomplished through tool design, selection, and installation, while considering the task and the conditions in which the task is performed.

Tradeoff Between Different Physical Stresses in Tool Selection

Power hand tools having similar operating specifications are sometimes available in alternative configurations. In the case of nutrunners, this often means choosing between in-line, pistol-grip, and right angle configurations that perform similar functions. These alternative configurations are illustrated in Figure 1. Often process engineering requirements make no distinction between which configuration is needed. Selection sometimes in practice is a function of availability rather than ergonomics. Awkward postures can sometimes be avoided by selecting alternative power hand tool configurations.

Although there is research available with respect to posture and perceived exertion associated with operating these power hand tools at various locations, there is little information concerning use of these power tools when considering the tradeoff between posture and force. An example is provided by the selection of an in-line nutrunner rather than a pistol-grip nutrunner for operation on a horizontal work surface. The tradeoff between additional grip force necessary for operating an in-line power tool in one posture and the reduced hand force offered by the pistol-grip tool in another posture is not known.

Torque developed at an in-line power hand tool spindle (T_R) must be overcome by tangential shear forces between the hand and the handle (F_S). These shear forces are proportional to the compressive grip force (F_G) and the coefficient of friction between the hand and the handle (See Figure 1). Alternatively, hand force (F_P) needed to react against a pistol-grip nutrunner torque reaction force is proportional to the ratio between spindle torque (T_R) and the tool handle length (L_P). The tradeoff between the force necessary for operating a pistol-grip power hand tool and an in-line hand tool for the same torque (T_R) is not known. The hand force for a right-angle nutrunner is pre-positional to the ratio between spindle torque (T_R) and to length (L_R). Since (L_R) is often greater than (L_P), a right-angle nutrunner will require less hand force than a pistol-grip nutrunner for the same torque level. There is little data available that considers the tradeoff between hand force and posture associated with each tool configuration.

Table 3. Power hand tool mechanical properties affected by certain tool parameters

Tool properties	Tool parameters affecting tool properties
Load	Center of gravity location Tool mass Use of counterbalance or articulating arm Power line installation
Handle size	Type of grip needed (power, pinch)
Handle shape	Type of grip needed (power, pinch)
Handle orientation	Type of grip needed (power, pinch) Distribution of load Work location
Feed force	Type of fastener head Type of fastener tip or drill bit Work material
Sound level	Tool speed Power Work material Tool location
Reaction torque	Spindle torque Tool and handle length Stiffness of joint Torque reaction bar
Vibration	Tool weight Work material Abrasive material Tool speed Tool power Handle location Moment of inertia

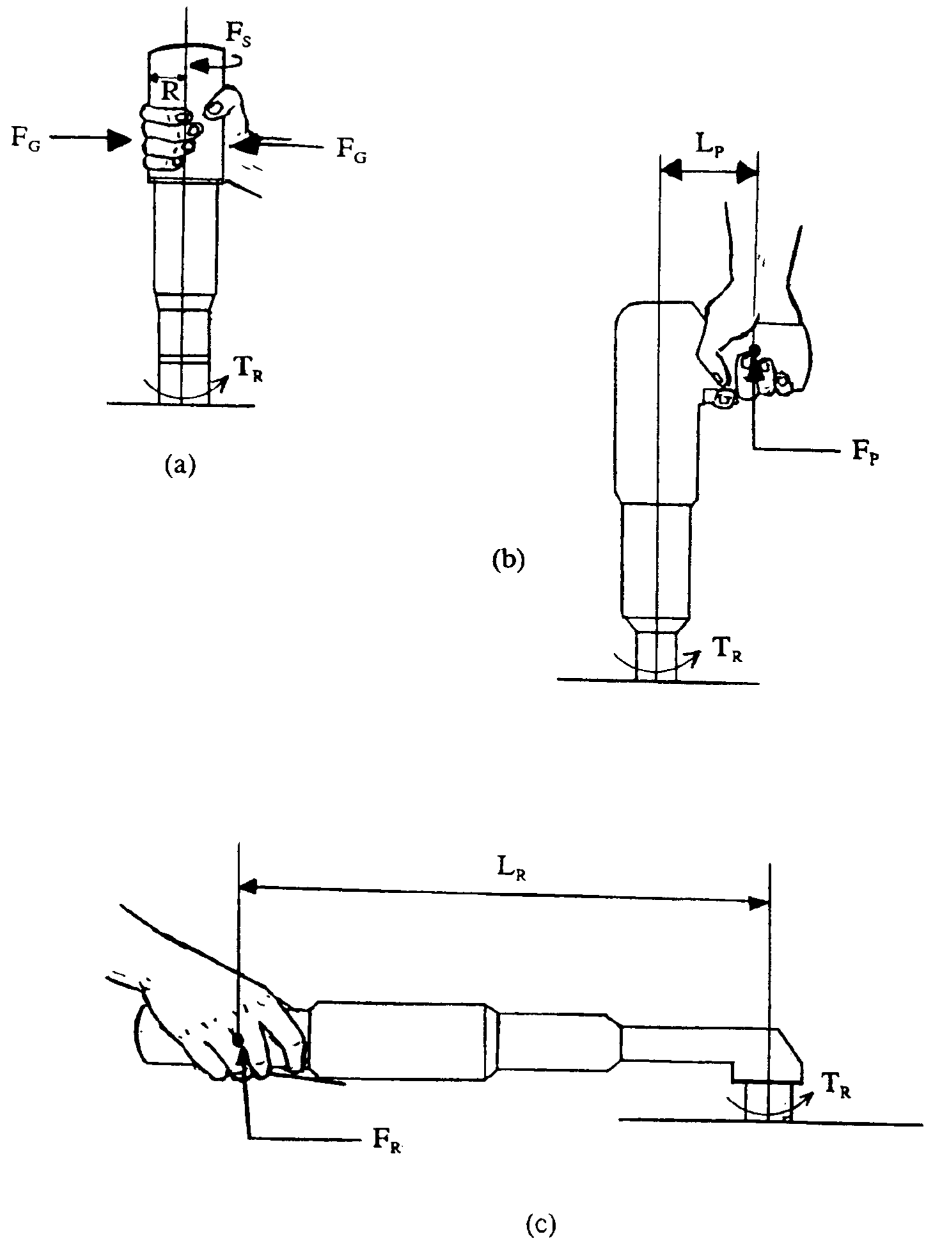

Figure 1. Hand forces associated with alternate power hand tool configurations; (a) in-line, (b) pistol grip, and (c) right angle.

3 ENGINEERING CONTROL AND DESIGN CONSIDERATIONS

This section addresses research in the area of control technology necessary for preventing or controlling musculoskeletal stress factors. This research includes research tool design, component design, joint fastening engineering and subsequent manufacturing methodology, and testing as it relates to physiological stress.

Engineering Controls

Engineering controls use engineering principles in equipment design and retrofitting for preventing, controlling, and decreasing the occurrence of physical hazard exposures. Engineering controls applied to power hand tools involves the consideration of tool, component, and workplace technologies. The objective is to control recognized hazards and prevent adverse effects resulting in fatigue, discomfort, and work-related musculoskeletal disorders.

Tool and Workplace Factors as they Relate to Controls

The following is a list of areas recognized for consideration, analysis, and implementation of controls for WMSDs:

- Posture
- Exertion/Force
- Contact pressure
- Handle friction
- Gloves
- Center of gravity (COG)
- Tool Location
- Tool activation and throttle
- Reaction Torque
- Balancer and Suspension
- Vibration

Posture

It is often recommended to avoid tools that require working with the wrist to be flexed, or hyper-extended, to have or ulnar or radial deviation when a specific job is performed.

Tools that require the forearm to be rotated while the wrist is bent are also not recommended. Neither should tools require operators to work with the elbow above mid-torso height or require work with the hands down behind the shoulder line in the sagittal plane. Generally, it is recommended that to the elbow remain at the side of the body to avoid extreme rotation of the forearm, to avoid extreme deviation of the wrist side to side, and to avoid palmar wrist flexion (towards the palm of the hand) or extreme wrist extension (towards the back of the hand). Awkward postures can often be avoided by selecting the appropriate tool for the particular work location.

Exertion/Force

When frequent exertions are necessary, the required forces should be reduced. Sometimes reducing the force requirements has the adverse effect of increasing the number of repetitions necessary for accomplishing a task. For example, if a small, light die grinder is used, the load is reduced, but the lighter grinder requires more force and repetitions than would a heavier angle grinder. When decreasing the time required to perform an operation, it is important not to increase the number of repetitions made in a work cycle.

Force can also be reduced by elimination of weight from tools and handled parts, or by provision of mechanical aids for handheld tools, parts, and materials. Reaction torque is affected by the types of fasteners and tool power settings. Increasing friction between the hand and objects grasped can also reduce forces. If force is required for simultaneously gripping while pushing or pulling, a flange at the end of the tool should be provided to reduce slippage and possibly to decrease the grip force requirements.

Contact Pressure

Acute contact pressure, and hence mechanical stress concentrations in the hand, can be reduced by increased handle sizes, elimination of sharp edges, and use soft compliant coverings on handles. Handles should be as large as possible, while permitting comfortable fit in the hands, but not so large as to diminish strength. The size of the handle depends on the force and dexterity requirements of the task. A smaller handle is necessary for a light, precision, manipulative task than for a forceful one requiring gross movements.

Handle Friction

Sufficient friction should be present between the handle and the hand to provide a secure grip and prevent slippage. The frictional characteristics of the handle affect the grip force needed to maintain control of the tool, and the ability needed to exert torque. Surfaces that do not provide adequate friction require greater grip force, which may result in greater effort and even loss of tool control. The amount of friction depends upon the coefficient of friction between the hand and the material of the object grasped. Some materials have greater coefficients of friction and, consequently, better frictional characteristics than others (Buchholz et al. 1991). Coefficient of friction of palmar skin is complex, but is not independent of normal force, and can decrease with increasing force. When surfaces are coated with oil and other contaminants, palmar skin coefficient of friction may decrease, and coefficient of friction is affected by material texture (Bobjer et al. 1993).

Gloves

Hand tool operators often wear gloves to protect their hands. Gloves affect the force available for gripping handles. While gloves may increase friction, they do negatively affect hand forces by adding to the force necessary to oppose the resistance of the glove. A decrease in grip strength by as much as 15% - 20% has been observed when gloves are worn (Hertzberg 1955; Lyman 1957). On the other hand, a 20% to 30% increase in the ability to prevent objects from rotating or sliding out of the hand was reported when gloves were worn (Riley et al. 1985). The potentially adverse effects from glove usage can be minimized by the provision of properly fitting gloves, and ones that protect only as much of the hand as necessary.

Center of Gravity (COG)

As a general rule, it is recommended that the center of gravity of a hand tool should be aligned with the center of the grasping hand so that the hand will not have to overcome rotational moments, causing the tool to rotate the operator's wrist and arm. It is not too difficult to determine the center of gravity of a hand tool. The center of gravity is the intersection of plumb lines dropped when the tool is suspended from two different points. The center of gravity of the tool should be determined with the tool fitted with all its attachments, including air hose, couplings, and sockets. Forces introduced from unbalanced tool installations can sometimes be eliminated by changed extensions and adapters, relocated attachments, or suspended airlines. If the tool center of gravity is not aligned with the hand, a hand tool can be suspended from a counterbalance.

Tool Location

A power hand tool should be installed so the operator can lay it on the ground, hang it from the ceiling, or attach it to some fixed supporting structure, rather than holding it in the hand. If a fixed support cannot be obtained, a belt, instead of the hand, should support the tool. If a heavy power hand tool requires support during operation, then it is considered better to let one hand do the holding, while the other does the operating, as opposed to letting one hand simultaneously hold and operate the tool. Power and air cabling should not interfere with the operation and/or manipulation of a tool.

Tool Activation and Throttle

Push-to-start activated power hand tools free the operator from having to squeeze a trigger or lever, but they can increase feed force requirements. The level of feed force required can be addressed by selecting tools that minimize the activation force needed for operating push-to-start tools. Tool throttles should not concentrate forces, but distribute forces in the finger segment and among several fingers. Lever triggers should not produce contact stresses or pinch points. Levers should take the shape of the handle when fully pressed. Levers should be at least as long as the hand.

Reaction Torque

Methods for minimizing reaction torque include use of long reaction arm tools, such as a right-angle nutrunner rather than a pistol-grip nutrunner. Installation of torque reaction bars and use of torque absorbing suspension systems also minimize reaction torque. Reaction torque for in-line handles are absorbed by an operator directly grasping the tool. Increased grip force is needed to prevent the tool from rotating in hand. High friction handle surface can help reduce grip force demand. Short length pistol-grip handles that move the hand closer to the vertical center of gravity help reduce wrist torque when the tool is carried or positioned; however, the mechanical advantage offered by a longer handle for reacting against reaction torque is also reduced. Accessory handles can provide a grip for a second hand to hold a tool.

The Ford Motor Company has power hand tool operation guidelines that specify torque reaction bars on in-line power tools for torque levels greater than 3.2 Nm (VanBergeijk 1987). Torque reaction bars are required for pistol-grip nutrunners operating at torque levels greater than 6.8 Nm. Ford Motor Company practices limit a maximum measured operator reaction force of 220 N, or a maximum measured impulse of 220 Ns. Automatic shutoff tools are substituted for stall tools when torque is greater than 40.7 Nm.

Alternative methods for limiting reaction torque include (1) use of torque reaction bars, (2) installation of torque absorbing suspension balancers, (3) provision of tool mounted nut holding devices, and (4) use of tool support reaction arms. A torque reaction bar can sometimes transfer loads back to the work piece. Tools that are equipped with a stationary reaction bar adapted to a specific operation so that reaction force can be absorbed by a convenient solid object can eliminate completely reaction torque from the operator's hand. These bars can be installed on pistol-grip , in-line, and angle tools. The advantages from tool mounted reaction devices include the following: (1) all reaction forces are removed from the operator, (2) one hand operated pistol-grip and in-line reaction bar tools can be used rather than right-angle nutrunners which usually require two hands, (3) reaction bar tools can be less restricting on the operator's posture, (4) tool speed and weight are improved over right-angle nutrunners in most tool sizes, (5) reaction bars can improve tool performance. The disadvantages are that reaction bars must be custom made for each operation and the combination of several attachments for one tool can be difficult. Torque reaction bars also add weight to the tool and can make the tool more cumbersome to handle. Providing tools with torque reaction bars or using torque absorbing suspension systems can eliminate torque reaction effects completely, although these interventions are not always practical, especially when there is limited accessibility, manipulation restrictions, or no surfaces for reaction bars to contact. A shorter tool, however, can be used if a reaction bar is provided. Acceptance and use of these devices varies greatly. Use of impulse tools can help reduce reaction torque, but such tools also produce vibration and noise, which must also be considered.

Balancer and Suspension

Balancer spring tension should be adjusted so the operator does not have to counter more force than necessary. Balancers should be adjusted so that tool aligns as closely to the work area as possible to prevent unnecessary reaching. The counterbalance should not lift the tool when it is released so that the operator has to elevate the shoulder to reach the tool. Also situations where operators tend to work ahead or behind the assembly line should be avoided. A trolley and rail system should be installed if a tool is to be moved horizontally. Special attention may be required to assure that the balancer is attached directly above the work.

Overhead suspension devices are best suited for assembly operations that can use a spring balancer or air balancer. Floor or side mounted articulating reaction and support devices are also available. Articulating arms help support the tool weight, absorb reaction torque, and free the hands for other activities. Articulating arms, however, restrict freedom of motion and may require an operator to manipulate a greater mass and consequently react against greater inertial forces.

Vibration

Besides considering alternative tools that produce less vibration, proper maintenance on current tools can help prevent vibration caused from worn bearings, malfunctions, or inadequate lubrication. Unbalanced rotating shafts and disks generate excessive vibration. Tool speed and power settings can also affect a tool's vibration characteristics. Tool operators should avoid using long, loose extension shafts on rotating spindles.

These can introduce vibration in tools not normally considered vibrating hand tools. Modifications in work methods may affect vibration exposure levels, such as redesigned production processes the reduction or elimination of vibrating hand tools, redistribution of the work among workers, and use of external tool support devices for reducing grip force or eliminating the need to hold tools when in use.

Although vibration levels should be measured using accelerometers mounted near the location where the tool is handled, sometimes dominant frequencies can be roughly estimated. Experience has shown spectra for rotating power tools, such as sanders, grinders, and polishers, had large, distinct, dominant fundamental frequencies corresponding closely to 88% of the tool free speed (in rpm), divided by 60 (Radwin et al. 1990b). Harmonics were also present, but the magnitudes of the harmonics were far less than the fundamental frequency magnitudes. Manufacturer-supplied, free-running tool speeds may be practical for initially estimating the frequency where most of the vibration energy is contained for these rotary action tools. This may be useful in practice, for example, when vibration isolation gloves and accessories for specific power hand tools are selected. The fundamental frequency of the power tool may be compared with the frequency range provided by the protective device in isolation. This method, however, is not recommended to take the place of direct hand tool vibration measurement for worker vibration exposure assessment, as specified in hand-arm vibration exposure standards.

Vibration may be reduced by using resilient mounts on handles. Vibration isolation for limiting vibration transmission from power tools to the hands and arms has been made difficult by the vibration frequencies involved. It is possible for these mounts to resonate and amplify vibration rather than attenuate. Since attenuation occurs only when the vibration spectrum falls above the resonant frequency of the isolation system or material, or when the vibration frequency is less than the resonant frequency of the isolating material, the handle acts as a rigid body and no vibration is attenuated. If the vibration frequency is approximately equivalent to the isolator resonant frequency, the system will actually intensify vibration levels. Weaker suspension systems with lower resonant frequencies are often impractical because such a system is usually too flexible for the heavily loaded handles of tools like grinders. Handles loaded with high forces must be very rigid. Grinding tools typically run at speeds near 6000 rpm (100 Hz) making it difficult to have a resilient vibration isolating handle.

Silencers are effective in attenuating the high frequency noise caused by turbulent airflow. Compound grinding wheels are being developed that have a noise damping layer between two thin wheels to attenuate high frequency vibration and noise. High noise levels associated with riveting in an airplane parts plant, for example, can be reduced by the placement of plates against fuselage panels held in place with suction pads.

Tool manufacturers are being challenged to provide new power hand tool designs that minimize musculoskeletal stresses. Several manufacturers have already incorporated new technologies based on current ergonomics knowledge regarding power hand tools. A notable example is provided by power hand tools that are designed to produce reduced vibration. Examples of specific tool properties that are affected through design are listed in Table 4. As new knowledge becomes available, tool manufacturers need a means of getting information so they can produce state-of-the-art tools based on the latest technologies.

Table 4. Power hand tool design properties affecting physical stress factors

Physical factor	Design objectives
Tool load	Use of light weight and composite materials Optimum load distribution Optimum handle location
Handle size/shape	Optimum size handle Optimum handle shape Adjustable handle size
Handle orientation	Optimum angle Adjustable orientation
Work location	Optimum location for tool load, handle size, and handle orientation
Work material	Tool speed Bits and blades
Sound level	Motor Housing and suspension Mufflers
Fasteners	Fastener head design
Torque	Shutoff mechanism
Vibration	Motor mounting Tool balance and load distribution

4 SUMMARY/CONCLUSIONS

The information summarized in this report attempts to highlight the available research and current practices regarding ergonomics and power hand tool use. The identification of future research needs requires a consensus among researchers, power hand tool manufacturers, and industrial power hand tool users.

The proper design and selection of hand tools is a complex process of analyzing the work station, materials, and methods; of accounting for worker characteristics; and of considering all of the variations that may result from the process or the individual. To accomplish this it is necessary to identify and have an adequate understanding of the interrelationship of most, if not all, of the process variables. This information must be integrated to critically evaluate the physical characteristics of the tool and the location of its application.

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