An Ergonomics Guide
to
Hand Tools

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Contents

The AIHA Ergonomics Committee dedicates this book to the memory
of Erwin R. Tichauer, Sc.D., a respected pioneer in the field of
ergonomics and original member of the AIHA Ergonomics Committee.
Dr. Tichauer was co-author of the 1978 AIHA publication,
Ergonomic Principles Basic to Hand Tool Design.

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Introduction

Making and using tools is acknowledged as one of the most important evolutionary developments that sets humans apart from other animals,(1) although some lower primates make and use tools as well.(2) Our prehistoric ancestors fashioned rustic tools for crushing nuts from stones and for extracting edible roots from the earth from sharpened sticks.(3) The innovation of attaching handles to stones increased the radius and speed of stroke and provided additional kinetic energy for swinging and striking objects.(4) As technology advanced from sticks and stones to iron and wood, a great wealth of tools was produced for accomplishing countless tasks.

Numerous principles governed the making of tools and implements through the 19th century. During the Middle Ages, the distance across the palm to the tip of the outstretched thumb (hence the name "rule of thumb") was used to determine the size of handles for swords, files, and other implements. Although these principles were established either on the basis of intuition or through a long process of trial and error, subsequent biomechanical analysis has revealed that these empirically derived dimensions were practically optimal in many instances.(4)

As tools were adapted for particular crafts and trades, the craftsperson using the tool was intimately involved in its design process. Early American iron workers only forged tool blades, giving little thought to the design of the wooden handle or the rest of the finished tool.(5) Implement handles were custom fabricated by the very laborer who used them. Hand tools in museums reflect the individualized handle shapes and sizes (see Figure 1).

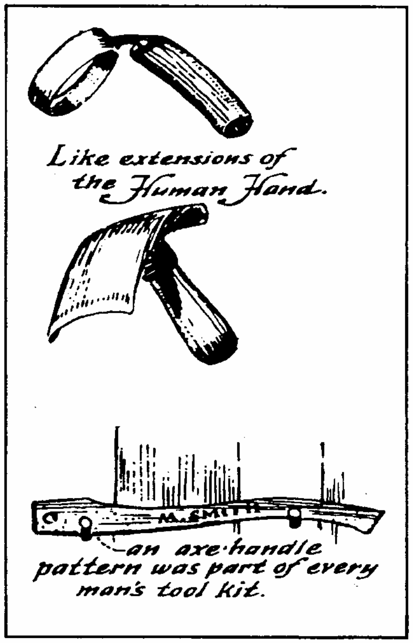

Figure 1—Museum hand tools. (From Slone, 1964; reprinted with permission.)

The Industrial Revolution brought hydropower and steam engines to the mills and factories. These new technologies substituted machine-powered tools for many manually powered hand tools. The power production tools of the early 1800s were too large to be held in the hands. But by the end of the 19th century the American inventor MacCoy(6) had developed a new kind of powered implement called a pneumatic tool, which was designed to be held and manipulated in the hands and was driven by compressed air. This is an early example of a portable power hand tool. It was not long before these tools were used for rock breaking and demolition. By 1918, Alice Hamilton concluded from her study of Indiana stonecutters who worked extensively with air hammers that the combination of vibration, cold temperatures, and how the tools were held and used was responsible for numerous symptoms, including numbness, vasospasms in the fingers, and manual dexterity deficits.(7) Air-powered tools were limited to chipping and stone cutting.

William Taylor recognized the benefits of selecting specific hand tools to accomplish productive work at the turn of the 20th century.(8) An important component of his scientific management plan included providing workers with the best tools for the job. Taylor studied shovel work and found that maximum work efficiency was achieved when shoveling a workload of 9 kg. The shovel size and shape for different materials were consequently adapted for this optimum load.

Assembly line production introduced highly specialized and repetitive work into the factories. Rather than use a wide variety of tools to complete an entire project, the worker repeatedly handled a relatively small number of tools to accomplish a specific task. Intensive use of a tool for short-cycle, repetitive operations exposed operators to the frequent motions and forceful manual exertions associated with musculoskeletal problems such as tendon and nerve disorders, which are often referred to as cumulative trauma disorders, or CTDs.(9,10) Epidemiologic investigations have shown that specific jobs involving highly repetitive use of hand tools have increased morbidity for CTDs.(11-13)

Modern power hand tools can operate at high speeds and are capable of producing very high forces. Furthermore, workers who use power hand tools often spend a large portion of the workday holding and operating them, sometimes in awkward locations and stressful positions. Because work performed with hand tools is usually not easily automated, since these jobs involve skilled and precise movements, hand tool manufacturers are challenged to provide a large assortment of power tools in a variety of shapes, sizes, power, and speeds. With so many tools to choose from, the best tool for the job is often not obvious. Improper selection, installation, or use that requires a tool operator to make substantially greater exertions than necessary might lead to muscle fatigue. Force demands that exceed an operator's strength capabilities can also cause loss of control, resulting in an accident, lost productivity, and sometimes injury.

A survey of state and federal agencies revealed that hand tool use was associated with 9% of all work-related compensable injuries.(14) The majority of workers were injured when they were struck by or struck against hand tools or when they overexerted themselves. Another report indicated that musculoskeletal injuries accounted for 24% of all reported hand tool injuries.(15) These injuries included disorders of the soft tissues such as the tendons, nerves, muscles, and connective tissues. Widespread use of hand tools for repetitive manual work has resulted in the need to protect hand tool operators from excessive exposure to physical stress arising from repeated motions and exertions, vibration, contact stress, and awkward work postures by selecting the best tool for the task.

It is not simply the use of a particular type of tool, but the way the tool is used that imposes physical stress on the tool operator. The relative effects of various physical stress factors involving work with hand tools are difficult to separate because many jobs using hand tools also involve extensive use of the upper limbs. For instance, hand tool operators may have to assume awkward postures dictated by a specific tool handle shape and workpiece orientation. The same tool may be used for frequent fast-cyclical tasks, resulting in exposure to repetitive exertions and motions.

Some power tools can also introduce vibration, and triggers may cause contact stress from sharp edges against the fingers or palm. The hands may also be exposed to cold air produced from pneumatic tool exhaust outlets. Despite all of these interrelated factors, it is generally agreed that physical stress, fatigue, and musculoskeletal disorders can be reduced by selecting the proper tool for the task. Using tools to minimize these adverse effects (that is, to produce low force demands on the hand, avoid awkward positions for holding and operating, and minimize shock, recoil, and vibration) is usually best for the job. Control of these factors depends on the particular tool and the specific tool application.

Some tools are now being marketed as "ergonomic," implying that operator fatigue or musculoskeletal disorders can be prevented simply by selecting these tools instead of other products without that label. There is no such thing as an ergonomic tool *per se*. Ergonomic principles should guide the selection, installation, and use of the right tool for the right application. Selection of tools should be viewed within the context of the specific job being performed. What makes sense in one situation can produce unnecessary stress in another. Considering the ergonomic aspects of using a particular tool for a particular job can prevent the adverse effects associated with using the wrong tool for the job.

The purpose of this guide is to introduce industrial hygienists, safety and health professionals, managers, and engineers to the basic ergonomic aspects of the selection, installation, and use of hand tools. A basic knowledge of ergonomics is assumed. Readers are referred to other ergonomics guides, including *Cumulative Trauma Disorders of the Hand and Wrist, An Ergonomics Guide,*(16) for a general discussion of ergonomics and work design.

Hand Tool Selection Criteria

Hand tools should be selected by considering both the physical process engineering requirements of the task being performed *and* ergonomics. When these aspects are considered together, the appropriate hand tool for a particular job should:

- Maximize performance;
- Enhance work quality;
- Minimize physical stress; and
- Prevent operator fatigue.

A variety of hand tools are capable of performing countless functions such as tightening screws, cutting sheets of metal, drilling holes, or grinding rough edges. Table I contains some examples of the various types of manual and power hand tools available.

Manufacturing engineers often specify hand tool requirements in terms of the production process, such as how fast a drill bit should turn, or how much torque should be applied to tighten a screw. Although these specifications affect the quality and performance of the physical process, engineers often fail to consider their effects on the hand tool operator performing the work. Not taking these effects into account can lead to impaired performance, operator fatigue, or musculoskeletal injury.

TABLE I. Common Varieties of Hand Tools

Manual Hand Tools	
Type of Tool	*Examples*
Wrenches	Handle-type wrenches (reversible ratchet, sliding tee, speeder, flex head) Nutdrivers Nondetachable socket wrenches Box wrenches (striking face, structural, double offset, ratcheting, heavy pattern, 15° offset) Open-end wrenches (engineer's, construction, structural, heavy "S", tappet, set screw) Adjustable wrenches Torque wrenches (scale, dial, micrometer adjustable, torque multiplier) Spanner wrenches
Pliers	Linemen's side-cutting pliers (regular, New England) Ironworkers' pliers Long-nose pliers Diagonal-cutting pliers Flat-nose pliers End-cutting pliers Slip-joint pliers Tongue and groove pliers Locking pliers/wrenches and clamps
Cutters	Wire cutters Cable cutters Bolt cutters
Striking Tools	Nail hammers Ball peen hammers Riveting and setting hammers (tinners' riveting, timmers' setting or paneing, machinists' riveting) Scaling and chipping hammers Bricklayers' hammers Prospecting picks
Striking Tools (Cont.)	Soft-face and nonferrous hammers and mallets (dead blow, wood, plastic faced, rawhide, copper) Magnetic hammers (bill posters', tack, upholsters) Engineers' hammers and sledges, double face Blacksmiths' hand and sledges, straight and cross peen Stone sledges and spalling hammers Hand drilling or mash hammers Bush hammers Woodchoppers' mauls Axes and hatchets
Struck or Hammered Tools	Cold chisels (flat, cape, diamond point, round nose) Hot chisels All-steel wood and ripping chisels Hand punches (prick, center, pin, starter, drift) Blacksmiths' punches (round and backing out) Drift pins (plug, taper, barrel) Star drills Brick chisels and brick sets Wood-splitting wedges Nail-puller bars Nail sets
Screwdrivers (slotted and recessed)	Stubby Square shank Cabinet Ratchet Specialty (jewelers', offset, magnetic tip, insulated, nonsparking, awl)
Vises	Machinists' Utility or workshop Automotive Wordworkers' Clamp-on Pipes Milling machines Drill presses

Clamps	C-clamps Machinists' clamps Deep throat C-clamps Welders' C-clamps Bar clamps Pipe clamps Well-drillers' clamps Web clamps Hand screws Spring clamps Miter clamps
Snips	Straight pattern snips Duckbill snips Pipe and duct snips Aviation snips Offset snips
Saws	
Drills	Hand drills Reamers

Power Hand Tools

Type of Tool	*Examples*
Threaded Fastener Driving Tools	Screwdrivers and nutrunners (pistol-grip, angle, in-line) Wrenches Impact wrenches Ratchet wrenches Tube nut wrenches
Abrasive 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	Circular saws Chain saws Reciprocating saws Panel saws Trim saws Routers Shears and nibblers
Hole Preparation Tools	Drills (angle, in-line, pistol-grip) Reamers Tappers
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 Rammers Scalers Engraving tools
Special-Purpose Tools	Cable-binding tools Clip squeezers Electrode dressers Lint or roll pickers Multiple spindle tools Paint mixers Tab set tools Tube rollers Wire-wrapping and unwrapping tools Wire-strapping tools

Ergonomic hand tool selection considers both the physical process and its demands on the tool operator. These two factors are not independent; they often interact. If the task requirement exceeds an operator's capabilities, task performance can be compromised. If an operator becomes fatigued, performance and quality will also suffer. Proper hand tool selection minimizes the demands on the tool operator while producing maximum work performance and quality. Selecting the appropriate tool to accomplish a particular task should be based on 1) process engineering requirements; 2) human operator limitations; and 3) workstation and task factors.

Process Engineering Requirements

Selecting the appropriate tool first requires finding one capable of performing the physical task. If the operation involves tightening a screw in an assembly task, for instance, process engineering requirements 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 to accomplish the task quickly and reliably at the desired quality level.

Process engineering requirements for hand tools may include specifications for:

- Load and force;
- Torque;
- Speed;
- Precision and tolerance;
- Bits, blades, and abrasives; and
- Power source.

Human Operator Limitations

Manufacturing process requirements often specify needs relating to the "working end" of the tool, such as socket size, spindle speed, or torque. It is just as important, however, to consider how these requirements will affect the tool operator at the "operator end." For example, a power hand drill operation that requires drilling a certain diameter hole in a specific material may specify 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 exertion of the hand tool operator, who must apply force against the handle to push the drill against the work material. The type of exertion needed is different if the drill has a pistol-grip handle, rather than an in-line handle, as Figure 2 shows. Operator exertions also depend on the orientation of a specific shaped tool with respect to the work. An operator drilling a hole on a horizontal surface, for instance, has to push a pistol-grip hand drill against the palm, but an in-line drill has to be gripped in the hand and squeezed while the tool is pushed against the surface to produce the same feed force.

The force applied against the work material to accomplish a task is only one type of force that affects the operator. Power hand tools also *generate* forces, which in turn act against the operator. The torque at a power screwdriver blade, for instance, transfers a force back to the tool handle. The human operator must react against this

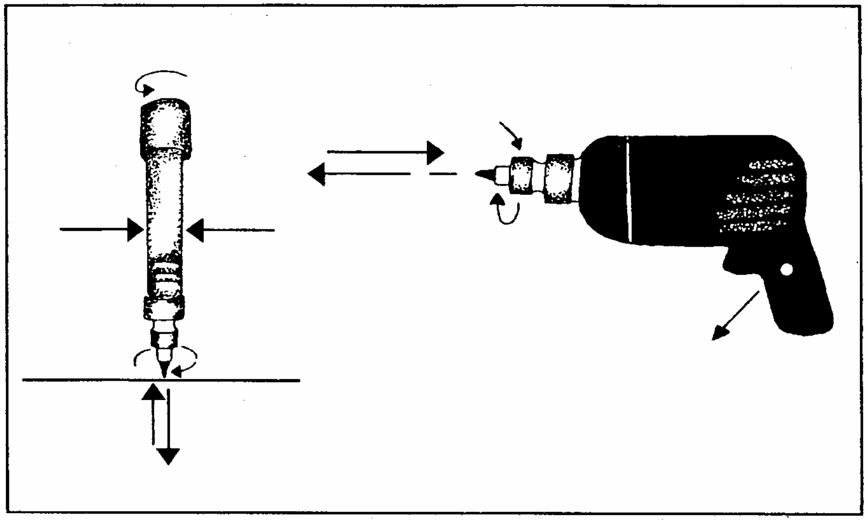

Figure 2*—Reaction force and torque act differently against the hand tool operator with a pistol grip and in-line power hand drill.*

force by exerting an equal and opposite force to hold onto the tool handle as the tool is operated (see Figure 2). The amount of force exerted and the way that force is directed back to the operator are influenced by the power hand tool capacity, its dimensions, and the handle shape.

How tool operators hold a particular hand tool might affect their posture and the manner in which the hand grips the tool. Posture and grip can introduce additional force demands at the operator's hands. The posture assumed when holding a particular tool alters the ability to use it by affecting strength capability. The handle size and shape can also limit an operator's ability to produce forces. The use of gloves can further affect the force available for gripping handles. Understanding and controlling these ergonomic factors are important for preventing injuries and for optimum work performance.

When selecting a hand tool, the following hand tool operator limitations should be considered: strength, anthropometry, and manual capabilities.

Both manual and power hand tools require operators to produce forces at varying levels. Manual hand tools may require exerting grip force to squeeze together tool handles such as pliers and cutting tools. Other manual tools require twisting, pulling, or pushing. Safe power tool operation requires that an operator possess the ability to adequately support the tool in a particular position and apply the necessary feed force while reacting against forces generated by the power tool. The capacity to produce forces is usually referred to as "strength." Strength is the maximum force an individual can produce.

The ability of hand tool operators to produce the required forces should be taken into account when selecting hand tools. An operator rapidly becomes fatigued when required to exert force at his or her maximum force generation capacity. The ratio between the force required and an individual's strength approaches 1 as the force requirement approaches an operator's strength. This proportion is related to the ability to sustain a given exertion and the onset of localized muscle fatigue. The greater the proportion of strength a repeated exertion requires, the quicker the opera- tor will become unable to sustain that exertion and the more rapidly fatigue will begin.(17) Tools should therefore be selected to minimize this proportion. This can be accomplished either by selecting tools requiring less force or by using tools in ways that enhance an operator's strength.

In addition to strength differences observed among individuals due to body size, gender, age, and training, an individual's strength is affected by body position, the direction and location from which a force is exerted relative to the body, the type of grip used to hold the tool, and the handle size. Operator strength capabilities change as the position of the limbs and the body change. For instance, arm muscles are strongest when pushing and pulling toward and away from the body (i.e., fore and aft) as opposed to across the front of the body (i.e., left and right).(18) The ability to exert maximum pulling exertions is affected by handle type and location. Pulling strength may be reduced by 37% when handle height is raised from 1.0 m to 1.75 m off the floor.(19) A study involving volitional torque exerted for different manual screwdrivers, vise grips, and wrenches found that the resulting torque magnitude is strongly influenced by the kind of tool and the posture assumed.(20) Grip strength diminishes when the wrist angle deviates from neutral. One study showed that grip strength decreased 27% for wrist flexion, 23% for wrist extension, 17% for radial deviation, and 14% for ulnar deviation.(21)

Handle shape and how good a handle couples with the hand can affect hand and arm strength. Handles that permit the greatest hand contact area and a power grip enable the greatest pulling forces.(19) A study of manual wrenches and screwdrivers found that tool handle shape affected volitional torque capacity.(22) Wrenches with circular grips and screwdrivers with triangular grips were associated with the greatest torque exertions.

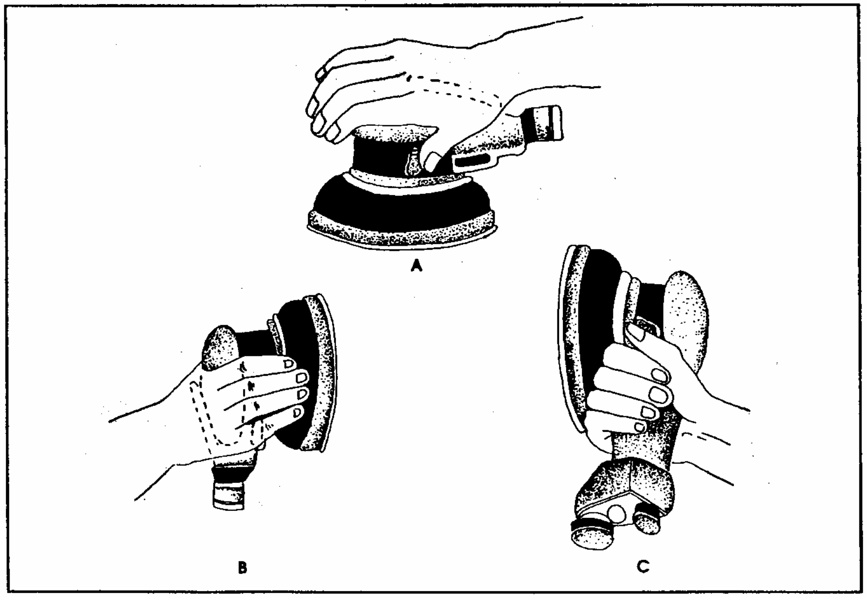

Figure 3—Tools are often used in ways not intended by the designer. The oscillating sander was designed to be held in the palm and operated on a horizontal surace (a). Using the tool on a vertical surface often requires the operator to grip the tool with a pincer grip in order to support the tool (b). A better alternative is to use a tool with a handle designed to provide a power grip (c).

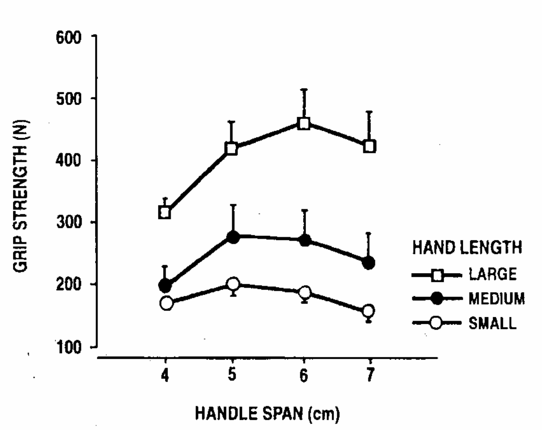

***Figure 4**—Each hand size has an optimal span across which the grip strength is maximized. Providing a variety of handle sizes or an adjustable handle size should be considered. (Oh and Radwin, 1993; reprinted with permission from* Human Factors, *Vol. 35, No. 3 (1993). Copyright 1993 by the Human Factors and Ergonomics Society. All rights reserved.)*

Grip strength depends on the type of grip used to grasp a handle. A precision grip or pinch grip is desirable for high precision, low force tasks such as using a jeweler's screwdriver. A power grip is assumed when all the fingers wrap around the handle.(23) Power gripping involves the large extrinsic flexor muscles in the forearm that provide high strength desirable for high force, low precision operations such as using a hammer. The hand is less capable of performing precise movements and exertions when using a power grip because of the large muscles used. Power grip strength can be as much as five times greater than pinch gripping.(24)

When high force is needed for precision work, consider using a power tool instead of a manual tool, allowing the tool to generate the force rather than the hand so the operator can use the small hand muscles to guide and position the tool precisely (e.g., substituting a power die grinder for a hand file). Some smaller power tools provide a precision grip by permitting the thumb and index to pinch the tool for positioning accuracy, as well as a pistol-grip handle to react against spindle torque and produce feed force. Tools designed for one type of grip are sometimes used incorrectly in a different manner, as with the power sander shown in Figure 3. Although this tool is intended for use on a horizontal surface, where the operator need not hold the tool because the surface supports the load, the operator has to handle the tool using a pinch grip when sanding on a vertical surface. A tool that permits a power grip is more suitable for sanding a vertical surface since this involves forceful exertions to support the sander.

Grip strength is affected through the biomechanics of grip from the relative position of the joints of the hand and by the position and length of the muscles involved. Consequently, grip strength is affected by the handle size.(18) If a handle is too large or too small, the strength of the hand is greatly compromised. The relative size of the hand with respect to the handle size is also important. The effects of grip size and hand size are illustrated in Figure 4. Small hands have less grip strength than large hands. Furthermore, the handle size resulting in maximum grip strength is smaller for small hands than for large hands.(25)

Handle dimensions should differ depending on whether they are intended for precision tasks, power manipulations, or carrying.(26) No one handle is practical for all practical tasks, and certain handles serve some objectives better than others. A panel of ergonomics experts recommended using a small diameter handle (8 mm–13 mm) for a precision grip and a large diameter handle (50 mm–60 mm) for a power grip.(27) In one study, handle diameters between 31 mm and 38 mm were considered optimum for a power grip.(28) Several studies recommended 50 mm as an upper limit diameter for handles used with a power grip.(29-31)

The particular finger or combination of fingers used also affects grip strength. The thumb, index, and middle fingers are the strongest fingers and they should be used to produce the most grip force. The ring finger and small finger are capable of less strength(32) and should be used for stabilizing handles rather than as primary force contributors. Sometimes tool operators handle tools in ways that take this into account. Swedish researchers observed that sheet metal workers held metal shear blades pointing inward toward the body, rather than the way that conventional shears are held, pointing away from the body.(33,34) Figure 5 illustrates this position. The maximum force of one finger depended not only on its grip span but also on the grip span of the other fingers.(35) Finger strength data revealed that this position allowed a greater span between the larger index finger and thumb than between the small finger and the palm, providing a handle size better suited for producing more force in each cut.

Sufficient friction must be present between the handle and the hand in order to provide a secure grip and prevent a tool from slipping. The frictional characteristics of the handle affect the grip force needed to maintain control of the tool and the ability to exert force or torque. Surfaces that do not provide adequate friction require greater grip force, which may require greater effort and even result in loss of control of the tool. The amount of friction depends on the coefficient of friction between the hand and the material or object grasped. Some materials have greater coefficients of friction and, consequently, better frictional characteristics than others.

Coefficients of friction measured between different materials and palmar skin(36) indicate that the friction necessary to prevent a handle with a smooth vinyl plastic covering from slipping may be as much as 1.7 more than a bare aluminum handle. Furthermore, 1.6 times as much friction is available for keeping a handle covered with adhesive tape from slipping when the hands are moist than when the hands are dry. Hands may become dry with repetitive handling of objects or evaporation due to airflow across the hands from air exhausts.

The population of workers using the tool is another important consideration. Strength is affected by age, gender, size, and training. The average age of the working population is increasing, and grip strength decreases for an aging population.(37) The maximum grip strength decreases to about 30% of its highest value by age 60 to 65.(38) Hand size and, consequently, strength capability are also related to gender.(39,40)

A worker's size can affect the posture he or she assumes when operating a hand tool. The ideal work location for tall workers might be too high for short workers. Location, orientation, and tool design must all be considered, along with the stature of the worker.(41,42) Whenever possible, the location and orientation for a tool should be adjustable to accommodate workers of different sizes. In situations in which the work location and orientation cannot be adjusted to suit the worker, consider selecting

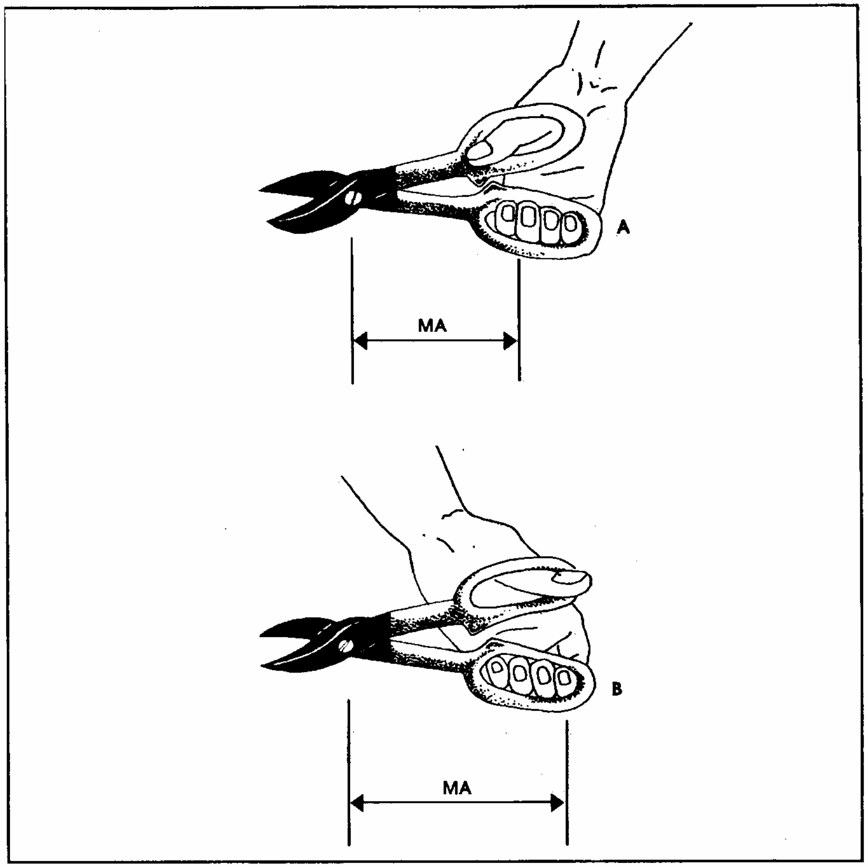

Figure 5—*Swedish investigators observed that shears were held pointed away from the body for precision tasks (a) and toward the body for forceful tasks (b). The reversed grip provides a longer effective moment arm (MA) and, hence, may explain the increased force.*

another tool. In cases in which the work specifications determine the tool design, it might be necessary to change the location or orientation of the work.

Tool handles that are too short may concentrate forces in the palms or make tools difficult to handle. Adequate handle size to accommodate the largest hands should be provided. A panel of ergonomics experts suggested a minimum tool handle length of 100 mm for precision gripping and 120 mm for power gripping.(27) If the fingers are inserted inside the handle, as with scissors or hand saws, adequate clearance should be provided for the largest hands. Often the 95 percentile hand width is used as a general rule. Additional clearance should be provided if the operator wears gloves.

Although about 10%–15% of the population is left-handed, many tools are only capable of being operated using the right hand. This can sometimes pose a problem since the dominant hand is usually stronger and more dexterous. One study found that right-handed people were less capable of producing non-dominant hand exertions than left-handed people.(43) Tools should be equally usable in the left hand as in the right.

Workstation and Task Factors

Ergonomic hand tool selection should consider the particular task and workstation where the tool is being used. Because of the way work location can affect the posture a hand tool operator has to assume, a tool may be appropriate for doing a job in one location but inappropriate for the same operation in another. A worker will assume a much different hand and arm posture using a pistol-grip nutrunner to drive a screw into a vertical surface at elbow height than when operating the same tool above shoulder height or below waist height.(44)

Physical stress associated with hand tool operation includes awkward postures, forceful exertions, repetitive motion, contact stress, and vibration. The consequences of selecting a particular hand tool for all these factors need to be considered to prevent upper extremity cumulative trauma disorders.(45) The physical stress level associated with chronic musculoskeletal disorders may be so small that a single occurrence seems harmless, but repeated exposure for a number of weeks, months, or even years could lead to an illness. The objective when selecting, installing, and using hand tools is to minimize operator exposure to each physical stress factor. All of these physical stress factors need to be considered together because reducing exposure to one factor might increase exposure to another factor.

Workstation task requirements for hand tools may include the following:

- Work location;
- Work orientation;
- Tool shape;
- Tool weight;
- Gloves;
- Frequency of operation;
- Tool accessories; and
- Work methods and standards.

Posture is affected by work location, work position, tool shape, and worker size. Although 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. Avoid selecting tools that require extreme postures to operate, such as flexing or extending the wrists. Tools shouldn't require operators to work with the elbows held above midtorso height or with the hands down behind the shoulder line in the sagittal plane. Awkward postures can often be avoided by selecting the appropriate tool for the particular location in which the work is performed.(45)

Tool handle shape and location of the work can affect the posture a worker must assume. A well-known example of how manual tools affect posture occurred when there was concern about deQuervain's disease at a Western Electric plant in the 1970s.(10) Workers were observed using sustained ulnar deviation of the wrists when soldering wires on a horizontal work surface with needle-nose pliers. The pliers were replaced by pliers with a bend in the handle, allowing the wrist to maintain a neutral posture with the pliers. A dramatic decrease in the incidence of the tendon disorder was reported. The bend made it unnecessary for the operators to repetitively ulnar deviate the wrist for sustained periods when soldering. The same tool, however, may not prevent the operators from working in an awkward posture if they are soldering wires on vertically oriented circuit boards. That depends on the particular use of the tool.

Force requirements for a job are often related to the weight of the tools being handled. The effort needed to grip an object is usually related to its weight.(46,47) Consequently, heavier tools require greater exertions. Hand tools used for precision operations should weigh as little as possible; Mital and Kilbom recommend less than 1.75 kg.(27) A counterbalance or tool support sometimes helps reduce the load when using heavy tools that are operated frequently.

When frequent exertions are necessary, consider reducing the forces required. The risk of developing a hand or wrist disorder increases significantly for workers performing highly repetitive and forceful exertions.(13,42) Sometimes reducing the force requirements has the adverse effect of increasing the number of repetitions necessary to accomplish a task. For example, if a small, lightweight hammer is used to bend steel tabs, the load in the hand is reduced, but the lighter hammer requires many more strikes. When high force is needed, consider substituting a power tool for a manual tool, especially if frequent exertions are necessary. Keep in mind, however, that by decreasing the time required to perform an operation, power tools may also increase the number of repetitions in a work period.

Force can be reduced substantially by substituting a power tool for a manual tool; the tool generates the force to do the work and the operator provides the force to support, position, and guide the power tool. Many jobs requiring frequent strong exertions should not be performed without the use of a power tool. Forces may also be reduced by eliminating excess weight from tools and handled parts or by providing mechanical aids for holding tools, parts, and materials. Increasing friction between the hand and objects grasped can also reduce the force required for gripping tools.

Contact stresses are produced when parts of the body come into contact with hard, sharp objects, resulting in forces being transmitted through the skin to underlying structures such as tendons and nerves. Some areas of the body are better suited to bearing contact stress than others. The skin on the back of the hand and sides of the fingers, for instance, is much thinner than that on the palmar side and less suited for exerting 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 the contact area decreases. Contact pressure, and hence mechanical stress concentrations in the hand, can be reduced by increasing handle sizes, eliminating sharp edges, and using soft, compliant coverings on handles. Handles should be as large as possible while permitting a comfortable fit in the hands. The actual size of the handle selected should also take into account the force and dexterity requirements of the task. A smaller handle is better for a light, precision manipulative task than a forceful one that requires gross movements. Also, if the handle diameter is too large, grip strength will be diminished.

Along with physical stress factors such as forceful and repeated exertions and stressful postures, vibration has been cited as a factor in chronic nerve disorders such as carpal tunnel syndrome.(11,12,48,49) Symptoms associated with prolonged and repeated vibration exposure are collectively referred to as "hand and arm vibration syndrome." These include vascular disorders, soft tissue damage, and neurological disturbances.(50) Vibration white finger, or Raynaud's phenomenon, is a vascular disorder resulting in vasospasms in the fingertips, which causes them to turn pale white.(51)

Other cumulative trauma disorder risk factors are adversely affected by vibration transfer to the tool operator's hand. Highly repetitive work can increase vibration exposure through accumulated doses.(52) Forceful exertions improve coupling between the handle and hand.(53) Repetitive operations increase vibration exposure time.

Work standards and individual work methods are additional factors affecting how hand tools are used. One study found that vibration syndrome was more prevalent among incentive workers than among hourly workers.(54) The report suggests that the intensity of incentive work results in increased vibration transmission and therefore exposure, presumably due to increased grip exertions and improved coupling between the hand and the power tool. Daily vibration exposure is directly related to the repetitive nature of the work or the number of operations per day. A direct relationship was observed between repetitiveness and vibration exposure.(55) Workers exposed to greater repetitive stresses were also subject to greater vibration exposures.

Fingers and hands can be exposed to cold when working in cold environments, such as in food processing or outdoors, when handling cold materials, or when air from pneumatic power tools exhaust vents blows across the hands, arms, or face. Handles made of conductive materials can conduct heat away from the hands, particularly in cold environments or when compressed air passes through pneumatic tool handles. Cold hands can reduce strength, manual dexterity, and tactile sensitivity.

Manual Hand Tools

Manual hand tools rely exclusively on the human operator as the power source. They are simple machines used to assist the bare hands in doing work. Manual hand tools include screwdrivers, pliers, wrenches, and hammers (see Table I on pp. 4-7). They often amplify muscles forces and contact pressure to enhance the operator's capability. The mechanical advantage provided by increasing moment arm ratios — greater kinetic energy available from increased moments of inertia, hard surfaces, added mass and ratcheting mechanisms — produces work not possible with a bare hand. The power outputs of manual hand tools, however, are limited by the exertions that can be generated by the human body. Although manual hand tools can protect the bare hand from mechanical insult, improper selection and use can introduce stresses into the hands holding and operating them.

As a general rule, muscle strength is proportional to its cross-sectional area. The larger the muscle, the more muscle fibers and the greater its force-generating capacity. When high force is needed, a hand tool that recruits the larger, more powerful muscles should be selected to provide the necessary output. Increased force demands should be met by using hand tools with increased mechanical advantages.

Torque strength improves when the mechanical advantage increases. A study of torque exertion capabilities found that greater torque was exerted using wrenches than using screwdrivers because of the increased mechanical advantage wrenches offer.(20)

The torque exertion capability of screwdrivers is also influenced by the improved mechanical advantage provided by larger grip diameters, if the handle diameter is not too great. Torque performance diminishes when handle diameters are greater than 50 mm.(29) A diameter of 40 mm is often recommended for screw-drivers(56-58) and even smaller diameters for more precise manipulations.(59) Larger diameter screwdriver handles transmit more torque; smaller diameter handles allow the tool operator to work faster with more precision.(60) Increasing the contact surface area between the handle and the hand increases the amount of torque that can be generated.(29)

There is usually a tradeoff between the increased mechanical advantage provided by a large tool vs. its weight and size and the operator's ability to manipulate and handle it. A tool that is too heavy and large may be too difficult to use to perform 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. For example, if the handle of a jeweler's screwdriver were so large or heavy that it was difficult to grasp using a precision grip, the large muscles used to manipulate it may not have the fine motor control needed, resulting in a stripped thread or a scratched surface. On the other hand, if a hand file is too small, more repetitive movements might be required to accomplish the same task than with a larger file. The type of grip suitable for operating a manual tool is often limited by the size of the tool. Select manual hand tools that optimize the strength an operator must exert in proportion to the ability to make necessary movements with speed and precision.

A rule developed in Sweden for selecting manual hand tools is to consider the tradeoff between force, precision, and frequency of use.(34,61) The rule recommends avoiding high-speed demands in combination with high force or precision and simultaneous demands of high speed, force, and precision. Take, for example, needle-nose pliers used in electronics assembly. Needle-nose pliers are often used for highly precise tasks such as positioning wires and small parts, but these operations require low force exerted at infrequent intervals. In another case, a large crosscut saw used for cutting wood planks requires moderate forces, and the tool is handled repeatedly for sawing but not with much precision. Based on the Swedish hand tool selection criterion, these tools are both appropriate for their respective tasks. In contrast, although the level of precision is low, a manual screwdriver used to frequently drive a great number of screws requires repetitive exertion of a high force. The combination of high force and repetitive tightening should be avoided, and selecting a power screwdriver can eliminate this situation. Always consider substituting a power tool for a manual tool when you need to perform high-speed tasks in combination with high force or precision.

Appropriate grips should be available on all manual tools. Grasped surfaces should be free of any protrusions and edges. Handles with pronounced ridges intended to fit the fingers may be too large or too small for an individual because of the large variety of size hands. Recesses for fingers, therefore, should be avoided since their spacing cannot accommodate most size hands and grasping a handle that does not fit the hand can concentrate compressive forces against the soft tissues underlying the fingers.(18,62) Sharp edges on tool handles can also injure the underlying tendons on the volar sides of the fingers (see Figure 6), contributing to a condition known as trigger finger — a stenosing tenosynovitis of the underlying tendons.(18,63)

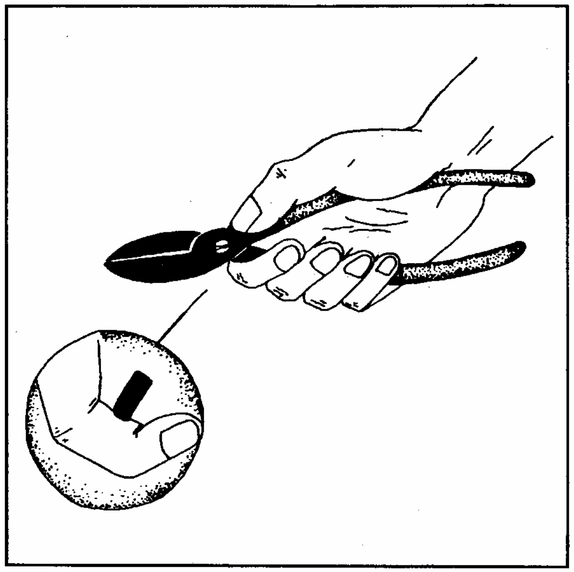

Figure 6—Sharp tool edges can concentrate mechanical insult from compression of underlying structures. The force should be spread over a larger area or directed to a less sensitive location.

It is better to use a flange at the end of the handle or a tapered handle to prevent slipping. High friction materials also prevent handles from slipping out of the hand.

Contact stress should be minimized, particularly when the hand is being used to produce the high forces sometimes required in operating a manual hand tool. A tool handle should distribute loads over as large an area of the palm as possible so forces are not concentrated in a specific region. If handles are too short, forces may be concentrated at the base of the palm. Handles should also be long enough to avoid stress concentrations in the palm. Handle length should be greater than the largest hand width. Contact with the sides of the fingers can irritate the digital nerves when the handles of scissors rub against the lateral side of the fingers.(64)

If a tool handle opens and closes, such as pliers or scissors, the size of the maximum opening span should be considered. Anthropometric limitations of the smallest hand should be taken into account, as well as finger clearances for the largest fingers. Additional clearance allowances should be made if the operator wears gloves. Tools should not have right- and left-handed models but be equally suitable for each hand. The correct hand tool may be misplaced, unavailable, or misused.

Some tools use latches and locks to lessen the requirement for a sustained grip. An example is a vise-grip. When this type of device is used, it is important to consider the amount of force necessary to actuate and release the locking mechanism. Poorly designed locks and releases can produce localized mechanical stress and pinching. In the process of reducing the stress from sustained exertions, locks and releases can introduce mechanical and safety hazards.(18)

Bent hammer handles were popularized by Bennett, who patented tool handles that bend at a 19° angle. Konz conducted a series of experiments using Bennett hammers.(65) The study concluded that although people preferred using hammers with bends less than 19° over straight handles there were no observed differences between their performance. Another investigation found that use of bent hammers resulted in less ulnar deviation than with straight hammers, but radial deviation was increased.(66) They also found the hammering performance with a bent handle was significantly worse on a vertical surface than on a horizontal one. Other studies concluded that bent handles are sometimes desirable for knives,(67) cooking tools,(68) and suitcases.(69) Although bent handles might eliminate certain stressful postures, the best handle angle probably depends on the exact tool, task, and orientation.(65)

The condition of tool repair can affect force requirements. A dull knife or a worn chisel or drill bit requires more force to use than if they were maintained properly.(62) Improperly maintained hand tools can introduce additional safety hazards. For instance, a wornout hammer head may rebound off the target and onto a finger.

Power Hand Tools

Power hand tools use an auxiliary power source external from the human body. Common power sources are pneumatic or air power, electric current, hydraulic pressure, gasoline motors, and explosives. The output of power hand tools is often many times greater than what can be produced by the bare hand, even with a manual hand tool. The hand, however, must react against the increased force and torque produced by power hand tools. Even the specific type of external power can affect an operator's exertions. A large electric motor, for instance, sometimes weighs more than a comparable air-powered tool. Power hand tool forces can be reduced by the mechanical advantage of handles and external suspension systems. Since the energy provided by power tools is normally greater than that produced by humans, the potential for injuries is greater. Despite this, one survey found power hand tools accounted for only 20% of all compensable injuries associated with hand tools.(14)

Although what was said for manual hand tools also applies for power hand tools, the use of external power brings additional ergonomics considerations, including the added load weight of motors, triggers for activation, reaction force and torque, power lines, balancers and other accessories, vibration, and acoustical noise.

Weight, Load Distribution, and Power Lines

The force necessary to support a power hand tool depends on the tool weight, its center of gravity, the length of the tool, and air hose attachments. Power hand tools should be balanced with all attachments installed. As a general rule, a hand tool's center of gravity should be aligned with the center of the grasping hand so that the tool does not rotate the operator's wrist and arm.(18) The center of gravity is the intersection of plumblines dropped from the tool, suspended from two different points.(4) Figure 7 illustrates a simple method for determining the center of gravity. When determining the center of gravity, the tool should be fitted with all its attachments, including air hose, couplings, and sockets. Forces introduced from unbalanced tool installations sometimes can be eliminated by changing extensions and adapters, relocating attachments, or suspending airlines. Consider suspending a hand tool from a counterbalance if the tool center of gravity is not aligned with the hand. A power tool should be suspended near its center of gravity to compensate for imbalance (see Figure 7).

Power hand tool installations should enable the operator to lay the tool on the ground, hang it from the ceiling, or attach it to some fixed supporting structure, rather than holding it when not in use. If a fixed support cannot be obtained, a belt can be

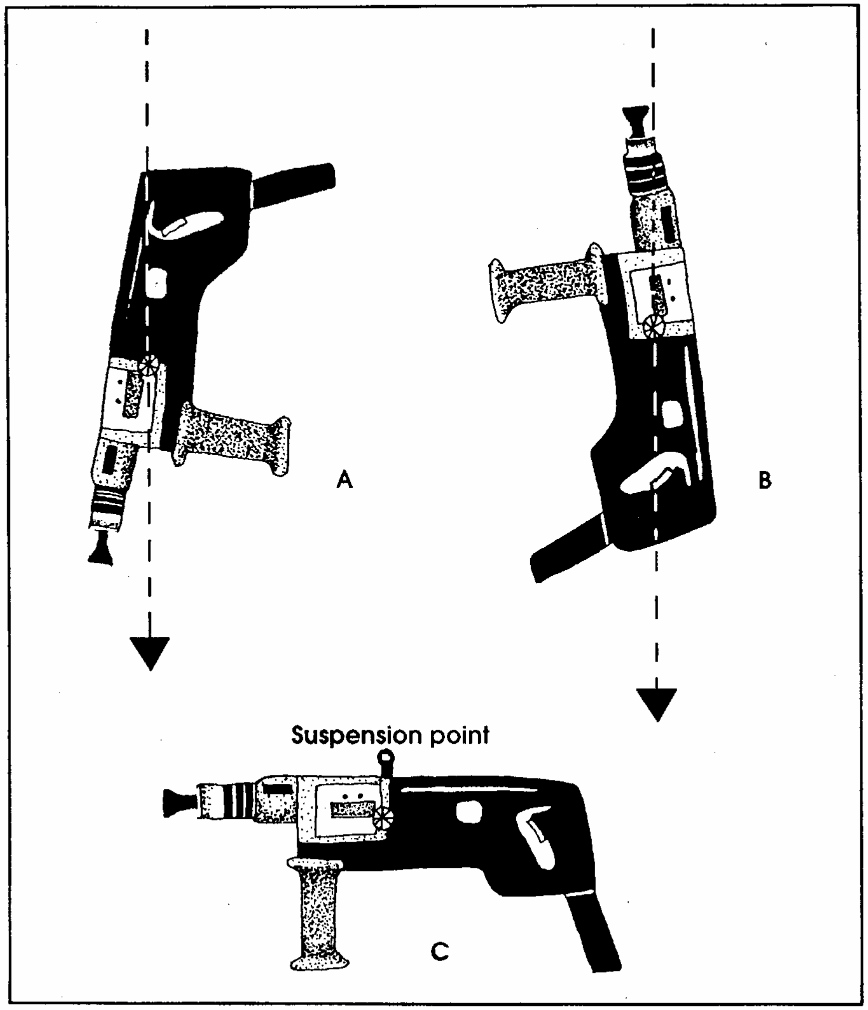

Figure 7—Method for determining the center of gravity: The tool is suspended first from one point (a) and the plumbline is marked on the tool. When it is suspended from a second point (b), the intersection of the first plumb line with the second is the center of gravity. Suspending the tool above the center of gravity allows it to hang stationary (c).

worn to hold it.(18) If necessary to support a heavy power hand tool, one hand should hold the tool while the other does the operating.(18) Power and air cabling should not interfere with the operation or handling of a tool. The added weight of air hoses, power lines, couplings, and adapters — which the tool operator must hold and carry — is often overlooked. Make tools as convenient to carry as possible. A worker should be able to carry them close to the body and with one hand.(18)

Psychophysical experiments provide some insight into the load that power tool operators prefer. When experienced hand tool operators were asked to rate the mass of the power tools they operated, tools weighing 0.9 kg to 1.75 kg were rated "just right."(70) Other psychophysical experiments showed that perceived exertion for a tool mass of 1 kg was significantly less than for tools with a mass of 2 kg and 3 kg.(71)

There is a tradeoff between a light tool and the benefit of added weight to performance in operations that require high feed force. The power available for a grinding task increases with increasing mass of the grinder. Reducing the grinder's weight increases the feed force the operator must provide and might increase the amount of time necessary to accomplish the task, consequently subjecting the operator to more stressful work and greater vibration exposure. Heavy grinding tasks should be performed on horizontal surfaces so the weight of the tool does not have to be supported by the operator. Heavy power tools should be suspended with counter-balancing accessories.

Triggers

Triggers extending far away from the handle make it necessary to use the distal finger segments. Using the distal phalanx to actuate a tool trigger contributes to tendon stress.(62) Trigger finger derives its name from the snapping movements resulting from stenosis of the tendon sheaths. Tool triggers should not concentrate forces but distribute them over a larger area on the finger segment or among several fingers. Lever triggers should not produce contact stresses or pinch points. Levers should conform to the handle's shape when it is fully pressed and ideally should be at least as long as the hand.

Some tools allow for multiple finger activation to distribute the load among the fingers. When precise trigger control is necessary, as with variable speed tools, four-finger control is not possible because some fingers are needed to stabilize the tool handle. Operators actually exerted somewhat less force when holding a pistol-grip nutrunner with a two-finger trigger than a similar tool with a single finger trigger.(25)

Throttle force is the force needed to overcome the resistance of a valve or close an electrical switch when activating a power hand tool. Safety features that shut off a tool when the trigger is released often make a spring mechanism necessary, which contributes to the throttle force.(72) The spring action means that the fingers must work against a spring force in addition to the force needed to activate the throttle or valve. Triggers operated repetitively should minimize throttle force. A panel of ergonomics experts recommended that the trigger force needed to activate a power tool be less than 10 Newtons (N).(27,73)

Feed Force and Reaction Force

In addition to supporting the tool load, power hand tool operators often have to exert push or feed force, or act against reaction forces. Feed force is necessary to start a threaded fastener, advance a bit, or keep a bit or socket engaged during the securing cycle. Feed force is affected by the work material and design of the tool, bit, or fastener. Large feed forces are sometimes needed when operating power tools such as drills and screwdrivers. Repetitive or sustained exertions associated with these operations should be minimized. Drill feed force is affected by the drill power and speed, bit type, material, and diameter of the hole drilled. Power screwdriver feed force may be affected by the fastener head and screw tip used. A slotted or Phillips head screw generally requires more feed force than a torx head screw. Self-tapping screws require more force than screws tightened through pretapped holes. Material hardness is also a factor in self-tapping screws and drilling. Feed force requirements also increase as torque level increases for cross-recess screws. Allowances should be made for these factors.

Push-to-start activated power hand tools free the operator from having to squeeze a trigger or lever, but they can require more feed force to start. Select tools that minimize the activation force needed to operate push-to-start tools. A flange, as shown in Figure 8, at the end of in-line handles helps prevent the hand from slipping during feed force exertions.(47)

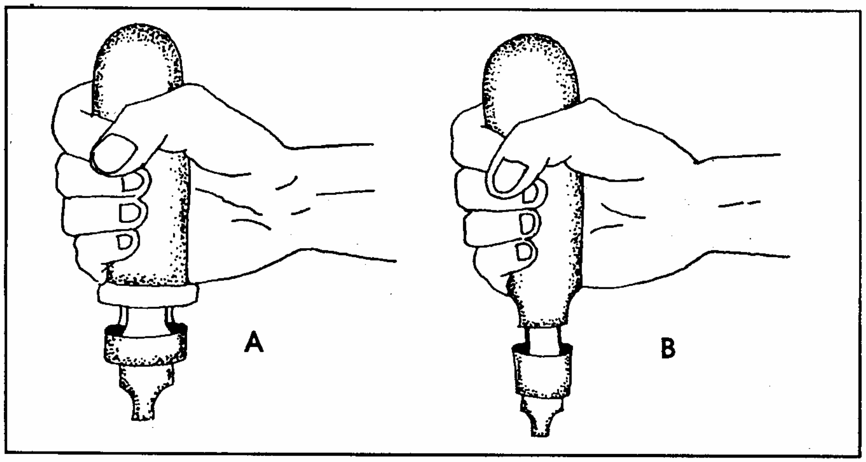

Figure 8—Flanging the end of an in-line tool reduces the grip strength needed to provide a given thrust by allowing that force to be supplied directly against the flange (a) rather than by friction with the tool handle (b).

Operator exertions made in providing feed force for a pistol-grip screwdriver or drill are affected by the location of the hand relative to the spindle. Figure 9 illustrates the forces acting against the hand. When high feed force is needed, hand force can be minimized by using pistol-grip handles that are in line with the tool spindle.

Reaction torque is produced by nutrunner spindle rotation and is affected primarily by the spindle torque output and tool size. Nutrunner spindle torque ranges from less than 0.8 Newton-meters (Nm) to more than 700 Nm. A tool operator opposes this reaction torque while supporting the tool and preventing it from losing control. This torque is transmitted to the operator as a reaction force through the moment arm created by the tool and tool handle. The three major operating modes for nutrunners include: 1) ratcheting clutch; 2) stall; and 3) automatic shut-off. In a stall tool the operator directly controls maximum reaction torque time by releasing the throttle, which can last as long as several seconds. Stall tools tend to expose an operator to reaction torque the longest. Although clutch tools limit reaction torque exposure, ratcheting clutch tools can expose workers to significant levels of vibration if they are used frequently.(55) The speed of the shut-off mechanism in automatic shut-off tools controls exposure to peak reaction force. Consequently, automatic shut-off tools have the shortest torque reaction time since these tools cease operating immediately after the desired peak torque is achieved.

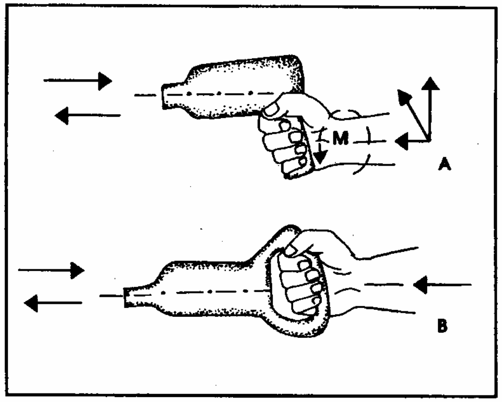

Figure 9—The use of a pistol-grip tool (a) results in a torque (M) at the wrist, since the push force is not coplanar with the reaction force. High feed forces increase this moment. Using a tool with a high grip (b) can reduce or eliminate this torque.

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 may approach zero with free-running nuts or be rather significant, as when locking nuts, thread interference bolts, or thread-forming fasteners are used. The fastener brings the clamped members of the joint into initial intimate contact, then continues to draw the parts together until they form a solid joint. When the joint becomes solid, continued turning of the nut proportionally increases the 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 to rise at a fixed rate until peak torque is achieved, which is the clamping force of the joint. Figure 10 shows representative power nutrunner dynamics. When operating automatic air shut-off right-angle nutrunners, forearm muscle reflex response during the torque-reaction phase was more than four times greater than the muscle activity used to hold the tool and two times greater than in the rundown phase.(74) Flexor EMG activity during the torque-reaction phase increased for tools with increasing peak spindle torque.

Threaded fastener joint stiffness ranges from hard to soft. Joint stiffness depends on the particular combination of all parts including gaskets, spacers, washers, and fasteners. Hard joints are formed by bringing two solid objects together (e.g., attaching a pulley to an auto crankshaft). Soft joints involve objects with more elastic properties such as joints containing gaskets, rubber grommets, sealants, or two parts drawn together. "Torque rate" — used to quantify joint stiffness — is defined as the angular rate of torque build-up to the resistance of tightening. It is measured by spindle torque vs. spindle rotation, in units of Newton-meters per revolution (Nm/rev). For example, the same nutrunner can be used in a hard joint at a torque rate of 600 Nm/rev or in a soft joint at a torque rate of 6 Nm/rev. Torque build-up time is much greater for the soft joint than for the hard joint. Joint stiffness is sometimes quantified in terms of "joint rate," measured by the spindle rotation in degrees needed to achieve the specified torque, once the joint components have been drawn together. Using joint rate, the specified torque is reached with less than 60° spindle rotation for a hard joint and more than 360° for a soft joint.

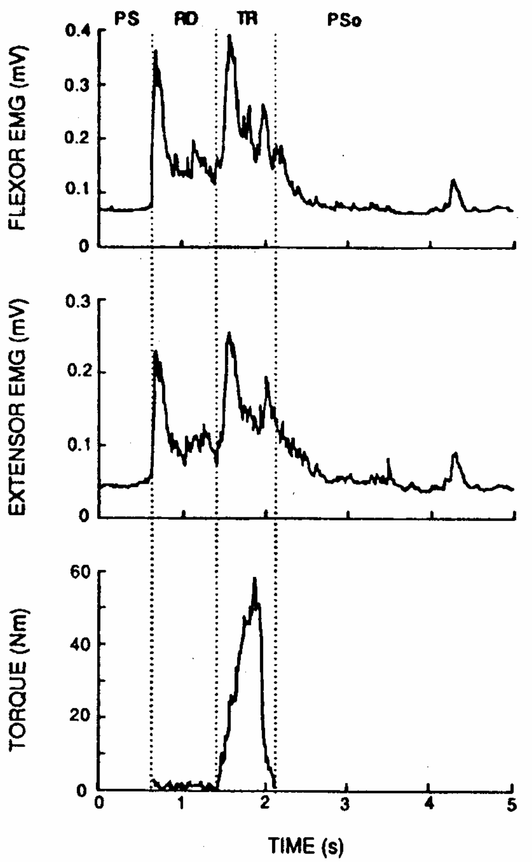

Figure 10—Representative nutrunner spindle torque output and associated forearm flexor and extensor rms EMG response for a 0.5-sec short torque reaction time. The prestart phase is indicated by PS, the run-down phase is indicated by RD, the torque-reaction phase is indicated by TR, and the post shut-off phase is indicated by PSo.

Methods for minimizing reaction torque include use of long-reaction arm tools, such as a right-angle nutrunner rather than a pistol-grip nutrunner, installing torque reaction bars, and using torque-absorbing suspension systems. Reaction torque for in-line handles is absorbed by directly grasping the tool. Increased grip force is needed to prevent the tool from rotating in the hand. High-friction handle surfaces can help reduce grip force demand. High-grip pistol handles reduce torque in the wrist when the tool is carried or positioned, and assist with exerting feed force, but the mechanical advantage of reacting against reaction torque is reduced. Accessory handles provide a grip for a second hand to hold a tool for reacting against torque.

As torque output increases, in-line power hand tools are usually unsuitable, and the additional support or mechanical advantage provided by a pistol-grip tool is needed (see Figure 11). Right-angle tools provide more mechanical advantage for

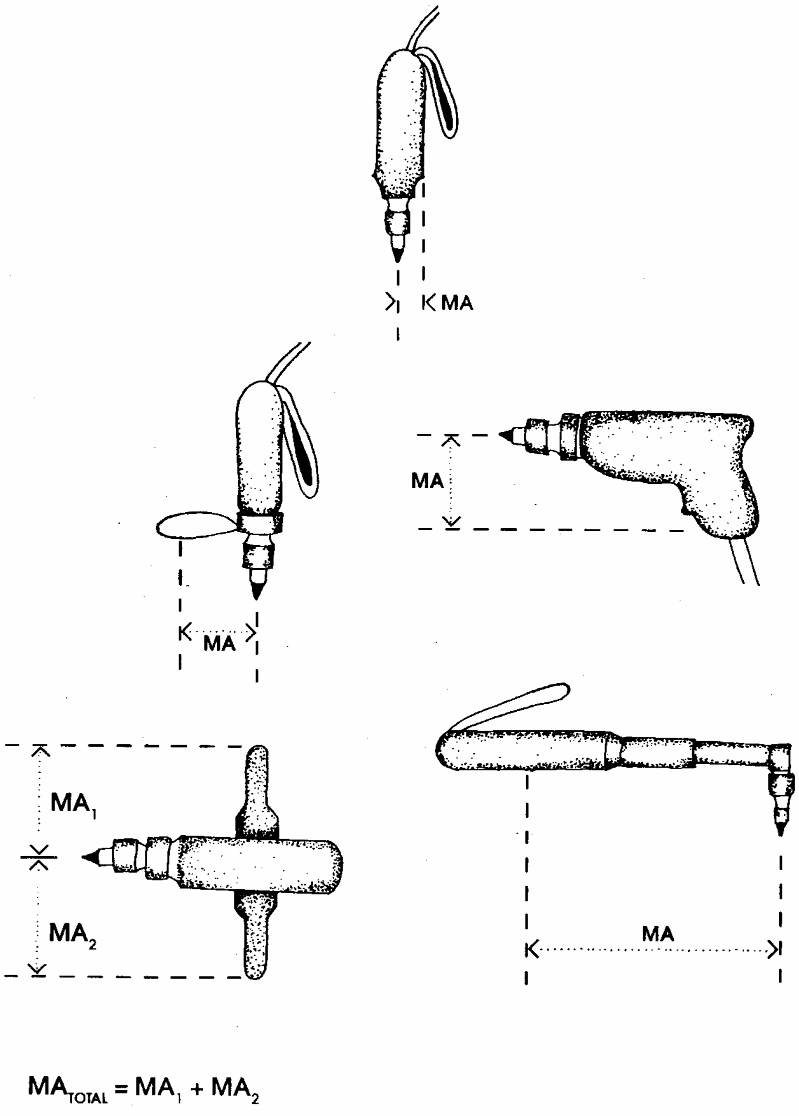

Figure 11—Selection of the tool shape depends on the torque requirements of the job and, hence, the associated reaction forces. Increasing the length of the moment arm (MA) increases the ability to react against the torque.

even greater torque requirements. Although the limits are not scientifically validated, the Ford Motor Company's power hand tool operation guidelines specify torque reaction bars on in-line power tool for torque levels greater than 3.2 Nm.(75) Torque reaction bars are required for pistol-grip nutrunners operating at torque levels greater than 6.8 Nm.(75) The hand force for right-angle tools should be no greater than 267 N.(75) Ford also limits the maximum measured impulse to 267 Ns, measured between the time when 44.5 N handle reaction force is exceeded and when force drops below 44.5 N after shut-off.(76) Automatic shut-off tools are substituted for stall tools when torque is greater than 40.7 Nm.(75)

There is a tradeoff between torque and posture when selecting nutrunners. Although operators using in-line power tools maintain a neutral wrist posture when working on a horizontal surface, high torque in-line screwdrivers require high grip force to keep the tool from slipping from the hands. Consequently, less force may be needed for a pistol-grip tool than for an in-line tool. A pistol-grip power tool, however, may require relocating the work or reorienting the work to avoid stressful wrist posture. Alternatively, a tool support reaction arm may be used to reduce grip and hand force.

Methods for limiting reaction force include: 1) using torque reaction bars; 2) installing torque-absorbing suspension balancers; 3) providing tool-mounted nut-holding devices; and 4) using tool support reaction arms. A torque reaction bar can sometimes be used to transfer loads back to the workpiece (see Figure 12). Tools that can be equipped with a stationary reaction bar adapted to a specific operation, so that reaction force is absorbed by a convenient solid object, completely eliminate reaction torque from the operator's hand. These bars can be installed on in-line and pistol-grip tools. Right-angle tools can also react against a solid object instead of relying on the hand and arm. Reaction devices 1) remove reaction forces from the operator; 2) permit pistol-grip and in-line reaction bar tools to be operated by two hands; 3) free the operator from restricting postures; 4) provide lighter weight than right-angle nutrunners; and 5) improve tool-fastening 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 may also add weight to the tool and can make the tool more cumbersome.

Torque reaction bars or torque-absorbing suspension systems can eliminate torque reaction effects completely, although these interventions are not always practical, especially with limited accessibility, manipulation restrictions, or lack of surfaces for reaction bars to contact. Accessibility restrictions might not be a concern with smaller tools when reaction bars are provided. Acceptance and use of these devices varies greatly. Impulse tools or impact wrenches can help reduce reaction torque, but vibration should be considered with these tools.

Handles

When experienced tool operators were asked to rate power tool handle sizes, all tools with handle circumferences smaller than 12 cm were rated "just right."(70) On a simulated power tool with a continuously adjustable handle span, the preferred handle size increased with greater hand size, suggesting that tool handles available in different sizes are preferable to one handle size.(25) The shape of the tool handle affects the mechanical advantage the operator has in reacting against tool forces. A noncylindrical handle can provide an improved reaction arm for in-line power tools.

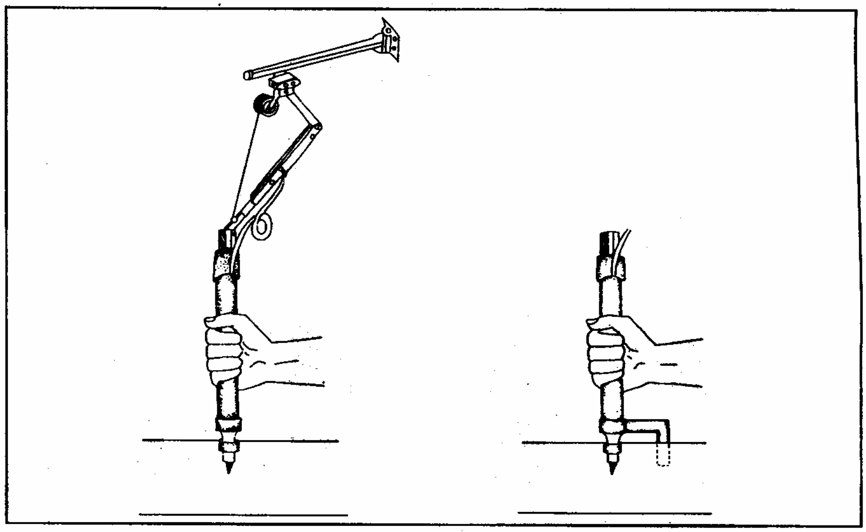

Figure 12—Torque reaction arms for in-line power tools.

Power tool handles include in-line, pistol-grip, right-angle, and various types of 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. Right-angle nutrunner operation often requires both hands, especially for the larger tools; however, usually only one hand is affected by reaction torque. The hand holding the handle farthest from the spindle reacts against the torque reaction force, providing tool support while the other hand produces push feed force.

Work Location

Power hand tool operators were asked to rate horizontal and vertical work locations on a continuous scale between 0 and 10.(70) The most acceptable vertical location for using tools was between 102 cm and 153 cm. The most acceptable horizontal location for tool use was within 38 cm of the worker. A 114-cm vertical work location had the minimum perceived exertion for driving screws with right-angle, pistol-grip, and in-line tools.(71) For driving screws on a vertical surface, the minimum perceived rating for pistol-grip tools was between 114 cm and 140 cm, and the lowest ratings for the pistol-grip and right-angle tools was 191 cm. When a horizontal work surface was midchest or elbow height, right-angle and in-line tools received the best ratings, but the pistol-grip tool received the best ratings for driving screws near midthigh height.(71) Figure 13 provides a flow chart for selecting a nutrunner based on subjectively acceptable work location and work frequency.(71)

Balancers, Articulating Arms, and Other Tool Accessories

Spring counterbalancers, air balancers, and articulating arms are available to counteract heavy tool loads. Special attention should be given to installing balancers so that minimal effort is needed to hold and use the tools in the desired

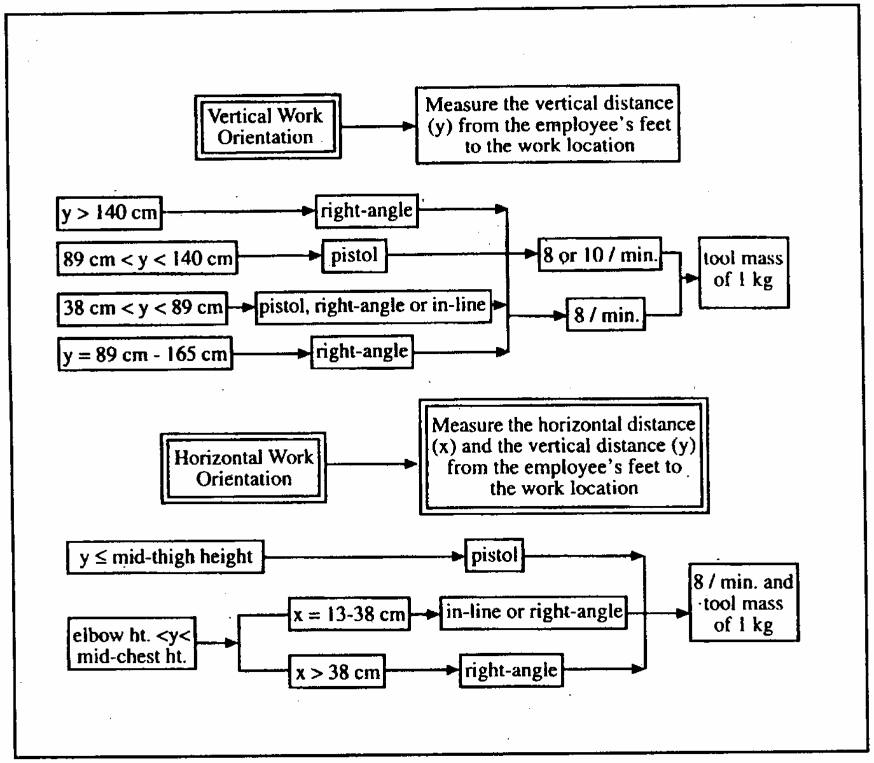

Figure 13*—Flow chart for selecting the tool shape, depending on work orientation (Ulin and Armstrong, 1992; reprinted with permission). The selection is based on maintaining neutral wrist and arm posture to the extent possible.*

work position. Spring counterbalances produce a force that opposes gravitational force, reducing the tool weight. If these balancers are installed incorrectly they may actually increase force. Spring tension should be adjusted so the operator does not have to counter more force than necessary. Balancers should be adjusted to align the tool as close to the work area as possible, to prevent unnecessary reaching. The counterbalance should not lift the tool when it is released, forcing the operator to elevate the shoulder to reach the tool. The tool should remain suspended at the same height as it was released. Also, avoid situations in which operators are working ahead of or behind the assembly line. Be sure that the balancer is attached directly above the work. A trolley and rail system should be installed if tools are moved horizontally.

Overhead suspension devices are best suited for assembly operations that are accessible from above. 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 might require an operator to manipulate a greater mass, limiting dexterity.

Vibration

Vibration can be a by-product of power hand tool operation, or even the desired action, as with abrasive tools such as sanders or grinders. Vibration levels depend on tool size, weight, method of propulsion, and the tool drive mechanism. It is affected by work material properties, disk abrasives, and abrasive surface area. Continuous vibration is inherent in reciprocating and rotary power tools.(77) 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 power, electricity, or hydraulics) also affects vibration. Vibration is also generated at the tool-material interface by cutting, grinding, drilling, or other actions.

Accessory attachments can be 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 that causes a tool usually not considered a vibrating hand tool to vibrate from the wobbling action of the rotating spindle. Tools that require maintenance or become unbalanced are also potential sources of vibration. Some tools are specifically designed to minimize vibration or may come fitted with vibration-isolated handles.

Handle location and the type of tool can have dramatic effects on the level of vibration transmitted to the operator. Vibration measurements from a large chipping hammer running at full throttle(78) indicated an acceleration ratio between the chisel end and rear handle of approximately 78:1. The same study found rear handle acceleration levels for a small stone chipper much larger with a ratio of 2.5:1, apparently due to the little mass isolation for this light tool.

Vibration may increase the risk of chronic tendon and nerve disorders by increasing the force exerted in repetitive manual tasks. Pneumatic hammer recoil was observed to produce a stretch reflex and muscular contractions in the elbow and wrist flexors.(79) Studies of the short-term neuromuscular effects have shown that hand tool vibration can introduce disturbances in neuromuscular force control, resulting in excessive grip exertions in holding a vibrating handle.(46) These studies demonstrated that grip exertions increase with tool vibration. Average grip force increased for low-frequency (40 Hz) vibration but did not change for higher-frequency (160 Hz) vibration. Since forceful exertions are a commonly cited factor in chronic disorders of the upper extremity muscles, tendons, and nerves, these studies show that vibrating hand tool operation might increase the risk of CTDs by increasing the grip force.

Vibration has also been shown to produce temporary sensory impairments.(80,81) Recovery is exponential and can require more than 20 minutes.(82) Workers sanding or grinding surfaces often periodically inspect their work tactilely to determine whether the surface is sanded to the desired level of smoothness. Diminished tactility may result in a surface feeling smoother than it actually is, resulting in a rougher surface than desired.

Unbalanced grinding wheels can generate periodic vibrational forces at a frequency equal to the rotational speed and in multiples of this frequency. Usually the frequency of the rotation speed dominates over the higher frequency vibration. When grinding wheel imbalance causes vibration, little is gained by using a machine that produces less vibration. The best method of reducing this type of vibration is to eliminate the imbalance and isolate the operator.

Vibration exposure for workers using vibrating power hand tools should be minimized. Alternative tools should be considered if they produce less vibration. Proper maintenance can help prevent vibration caused from worn bearings, tool malfunctions, or inadequate lubrication. Increasing or decreasing tool speed and power settings can also affect a tool's vibration characteristics. Vibration exposure levels may also be affected by modifications in work methods, such as redesigning production processes to reduce or eliminate use of vibrating hand tools, redistributing the work among workers, and using external tool support devices to reduce grip force or eliminate the need to hold tools.

Vibration levels should be directly measured by accelerometers mounted near where the tool is handled. Dominant frequencies can sometimes be roughly estimated. Spectra for rotating power tools such as sanders, grinders, and polishers have revealed large and distinct fundamental frequencies that corresponded closely to 88% of the tool free-running speed (in rpm) divided by 60.(83) Use of manufacturer-supplied free-running tool speeds may be practical for initially estimating the frequency containing most of the vibration energy for these rotary action tools. This may be useful in practice, for example, when selecting vibration isolation gloves and accessories for specific power hand tools.(84,85) The fundamental frequency of the power tool may be compared with the frequency range the protective device effectively isolates. This method is not recommended in place of measuring hand-tool vibration to assess worker vibration, as specified in hand-arm vibration exposure standards.

Compliant mounts on handles have not been shown to significantly reduce vibration. Vibration isolation techniques have been generally unsuccessful in limiting vibration transmission from power tools to the hands and arms. Isolation has been particularly difficult for vibration frequencies less than 100 Hz. This is because attenuation occurs only when the vibration spectrum rises above the resonant frequency of the isolation system or material. 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. Many grinding tools run at speeds near 6000 rpm (100 Hz), making it difficult to have a resilient vibration-isolating handle. Furthermore, if the vibration frequency is approximately equivalent to the isolator resonant frequency, the system actually intensifies vibration levels. Weaker suspension systems have lower resonant frequencies but are often impractical because they are usually too flexible for the heavily loaded handles of tools such as grinders. Handles loaded with high forces must be very rigid.

Acoustic Noise

Loud noises can be produced by power hand tool motors and the vibration of moving objects, such as a grinding wheel against a grinding surface. Pneumatic vane motors generate sound with major changes in airflow caused by pressure differences and compression of air as the vanes rotate. The sound usually 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 is another common source of noise. This is caused by the formation of dynamic turbulence inside the tool. If air flows past sharp corners or edges, the noise is enhanced.

Noise can be reduced by using tools with have vane motors that create less abrupt

changes in airflow. Silencers are effective in attenuating the high-frequency noise caused by turbulent airflow. Compound grinding wheels have a noise-damping layer between two thin wheels to attenuate high-frequency vibration and noise. High noise levels like those associated with riveting in an airplane-parts plant may be reduced by using placing plates against fuselage panels held in place with suction pads.

In Summary

The selection, installation, and use of hand tools should include ergonomic criteria in addition to physical process engineering requirements. The process involves accounting for human strength, anthropometry, and manual capabilities, as well as workstation and task factors such as work location, orientation, tool shape and weight, use of gloves, frequency of operation, tool accessories, and work methods. Selection of manual hand tools should consider tradeoffs between the tool size and weight, and the operator's ability to handle it. Adequate grips and handles should be provided, and manual hand tools should not cause operators to assume awkward postures or perform frequent exertions or motions. Power tools should be considered when use of manual hand tools increases physical stress. Power hand tool selection should consider weight and load distribution, triggers, feed force and reaction force, handle shape and size, work location, tool accessories, vibration, and acoustic noise. All this information must be integrated to critically evaluate the type of tool and how it is installed and used.

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