

CHAPTER

6e

**Biomechanical Aspects
of Hand Tools***Robert G. Radwin*

The mechanical relationships between hands, tools, and tool operation are important for understanding and controlling physical stress of tool operators. Hand exertions needed for many tool operations are affected directly by the selection of specific tools and accessories for the task. Although many of the recommendations in this chapter are based on years of extensive biomechanics research, others arise out of simple mechanical principles and reasonable assumptions about mechanical relationships between tools and their operators. The objective is to illustrate how the characteristics of a particular tool (such as size, shape, output, and accessories) and its manner of use (such as orientation or location relative to the operator) can significantly affect the effort needed for performing specific tasks.

Both manual (hand powered) and power (electric, pneumatic, or hydraulic) hand tools require that operators produce forces at varying levels. Manual tools may require exertion of forces to squeeze together tool handles, such as those of pliers and cutting tools. Other manual tools may require twisting, pulling, or pushing. Safe operation of a power tool requires that an operator support it adequately in a particular position and apply the necessary forces while reacting against the force generated by the tool itself. Force demands that exceed an operator's strength capabilities can cause loss of control and result in an accident or an injury. If improper selection, installation, or use of a power tool requires an operator to make substantially greater exertion than necessary, it may lead to muscle fatigue or a musculoskeletal disorder.^{1,5,28,39,40} Tools that are selected to minimize hand forces are usually the best ones for the task.

The discussion begins with simple manually operated hand tools, including screwdrivers and pliers. An investigation of the means by which different kinds of screw fasteners can affect forces in the hands is followed by a description of how selection and installation of power hand tools can control the static and dynamic hand forces associated with their use. Mathematical and biomechanical calculations are provided to enable interested readers to follow them and to impress other readers less concerned with how objective conclusions can be ascertained through mostly deterministic methods. These principles should be applicable to occupational health professionals in the selection and installation of tools. Designers and engineers should be able to adapt these calculations to new tools and job designs.

MANUAL SCREWDRIVERS

One of the most commonly used hand tools, the screwdriver, is available in various sizes and forms suitable for different types

of screws and work situations. A screw is tightened usually by grasping the screwdriver handle and simultaneously applying a torque while exerting a push force. The amount of torque, T , needed for tightening a screw depends on the kind of screw and the characteristics of the screw joint such as friction, screw diameter, thread, and clamping load.

The push force is often called *feed force*. Feed force, F , is the axial force applied against the screwdriver shaft that is required to thread the screw and keep the screwdriver blade seated. Numerous task-related factors affect feed force, including thread type (whether the screw is self-tapping or threaded), material hardness, thread size, and hole diameter. The choice of a particular size screwdriver can have a great effect on the hand exertion required for a task.

Handle length

A question often asked is how does screwdriver length affect hand force? Experience has found that a longer screwdriver handle generally results in less effort.³² This can be explained by considering the motions needed for tightening a screw. When a screw is tightened, torque is transferred to the handle, usually by rotating the forearm in combination with flexion and ulnar deviation of the wrist. The asymmetry of the hand, wrist, and forearm relative to the screwdriver's radial axis produces eccentric rotation of the handle and shaft along a horizontal displacement Δ from the vertical axis (Fig. 6e.1). The magnitude of this displacement depends on the particular action and anthropometry of the wrist.

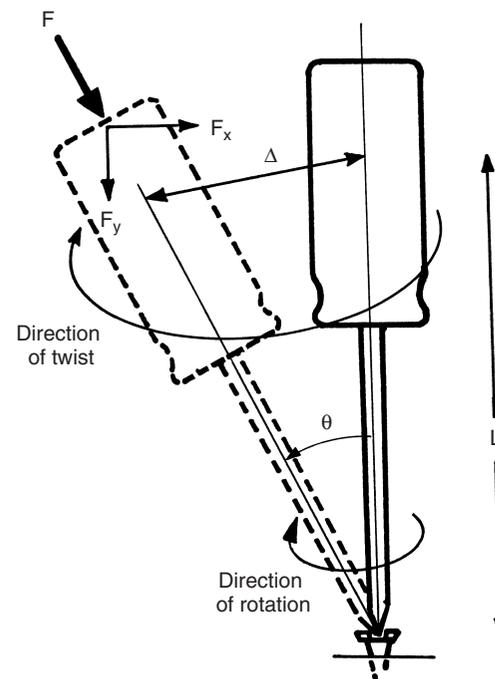


Figure 6e.1 Rotation and perturbation of a manual screwdriver when the handle is twisted in the hand.

This perturbation causes the screwdriver shaft to tilt to a maximum angle, θ , as the screwdriver rotates.

If screwdriver handle size, diameter, and shape and shaft diameter remain the same, hand and wrist rotation is unaffected by the shaft length, so the handle perturbation remains constant. Assuming that the handle displaces the same distance Δ from the axis of the fastener shaft (Fig. 6e.1), the maximum angle, θ , that the screwdriver shaft tilts as it is twisted can be described as

$$\theta = \sin^{-1}\left(\frac{\Delta}{L}\right)$$

Orthogonal feed force components (Fig. 6e.1) can be resolved into

$$F_y = F \cos\theta, F_x = F \sin\theta$$

If a screwdriver has a length, L , then the maximum component parallel to the fastener shaft is F_y :

$$F_y = F \cos\theta = F \cos\left[\sin^{-1}\left(\frac{\Delta}{L}\right)\right]$$

Solving for F ,

$$F = \frac{F_y}{\cos\left[\sin^{-1}\left(\frac{\Delta}{L}\right)\right]}$$

A consequence of this relationship is that if the required axial force component F_y remains constant, F decreases as L increases. Hence, the hand force exerted can be reduced by increasing L and using the longest screwdriver available. For example, if the shaft of a 6-cm screwdriver displaces $\Delta = 3$ cm, the feed force F needed to drive a screw is

$$F = \frac{F_y}{\cos\left[\sin^{-1}\left(\frac{3}{6}\right)\right]} = 1.15 \times F_y$$

Therefore, the maximum feed force can be as much as 15% greater than the axial force needed. If the screwdriver length is increased to 25 cm, the feed force needed to drive a screw would be

$$F = \frac{F_y}{\cos\left[\sin^{-1}\left(\frac{3}{25}\right)\right]} = 1.01 \times F_y$$

which decreases the force feed to only as much as 1% more force than is actually needed.

Of course, a very long screwdriver may not be practical under all circumstances. Clearance and spatial constraints may limit the size of screwdriver that can be used. Furthermore, a very short screwdriver can facilitate the precision grip needed for light precise work, such as that afforded with a jeweler's screwdriver.

Another way to limit the horizontal perturbation of a screwdriver as it rotates in the hand is by supporting the screwdriver shaft, as might be done when two hands are used. If the screwdriver were held straight by supporting the shaft with the fingers of the free hand, then the tilt angle θ remains close to 0 degrees

and $F_y \approx F \cos 0 \text{ degrees} \approx F$. This action therefore aids the operator by keeping the axial feed force requirements minimal and unaffected by screwdriver length. When high feed forces are required, screwdriver shafts should be long enough to be pinched or gripped by the other hand as a guide. Using a similar argument, the hand force needed for a nut driver should be mostly independent of the shaft length because the shaft is coupled to the nut, permitting concentric rotation with the handle despite the asymmetries of the hand and forearm.

Handle diameter

Another common question is how does a screwdriver handle diameter affect hand force? Several studies investigated the effect of handle diameter on the torque capability of the hand. A study involving volitional torque exerted for different manual screwdrivers, locking pliers, and wrenches found that the resulting torque magnitude was influenced strongly by the kind of tool and the posture assumed.²⁶ From a purely mechanical standpoint, a greater handle diameter should result in more torque at the screwdriver shaft for the same effort, provided that the frictional properties of the handles are similar and the diameter is not too large.

The diameter of a screwdriver handle plays a critical role in limiting a user's torque-generating capability. Large grip forces are often needed for sustaining a grip and for coupling the hand and the tool to prevent the handle from slipping. A simplified relationship between the torque and diameter illustrates the effect of mechanical advantage on torque:

$$T = S G = \mu F_G G$$

where T is torque, S is the shear grip force, G is the handle radius, μ is the coefficient of friction between the hand and the handle, and F_G is grip force.³² If F_G remained constant, torque would linearly increase as the handle diameter increased. As is well known, however, grip strength is not constant for all diameters but rather is affected by handle size.^{4,17,19} If a handle is too large or too small, the strength of the hand is greatly compromised. The relationship between cylindrical handle size and grip strength is summarized in Figure 6e.2.²⁹ Maximum grip force occurs around 6 cm. Consequently, the optimal diameter is one in which a further increase in diameter increases the mechanical advantage while simultaneously decreasing grip force. Research has found that this optimum depends on handle design, friction, gender, and hand size.³² Torque performance diminishes when handle diameters are greater than 5 cm,³³ and a diameter of 4 cm is sometimes recommended for screwdrivers.^{7,8}

Sufficient friction must be present between the handle and the hand to provide a secure grip, exert force or torque, and prevent a tool from slipping. Surfaces that do not provide adequate friction require greater grip force that may result in greater effort and even 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.

No one handle size is practical for all tasks, and certain handles serve some objectives better than others. A panel of ergonomics experts recommends using a small-diameter handle (8-13 mm)

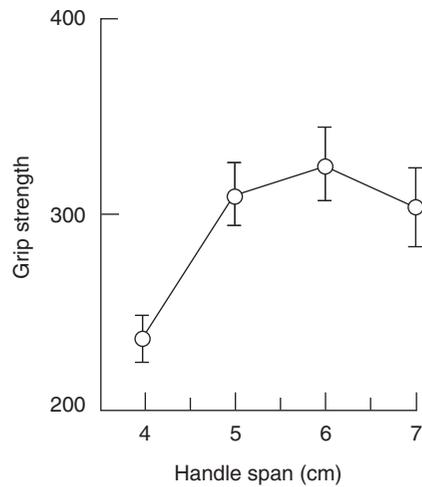


Figure 6e.2 Grip strength for a population of 29 subjects (19 university students and 10 factory workers). Error bars represent one standard error of the mean.

for a precision grip and a large-diameter handle (50-60 mm) for a power grip.²⁷ In one study, handles between 31 and 38 mm in diameter were considered optimal for a power grip¹²; several studies recommend 50 mm as an upper limit diameter.^{4,33,38}

SCREWDRIVER BLADES AND SCREW HEADS

Screwdriver feed force can be affected by the particular type of screw fastener head and screw tip needed.⁶ Self-tapping screws require more feed force than do screws tightened through pre-tapped holes. Material hardness and friction are also important factors to consider for self-tapping screws. Feed force requirements increase as the torque level increases for cross-recess screws.

Allowances should be made for all these factors. The three most common threaded fastener heads are slotted, Phillips, and Torx™ (Fig. 6e.3), each of which has different feed force requirements.

Slotted screws

The oldest and simplest type of screw head, the slotted screw, has a single slot across the entire diameter of the head. When a screwdriver blade is inserted inside a screw slot and rotated, contact is usually made at the two edges of the blade, as shown in Figure 6e.4. The size of the screwdriver width, w , limited by the radius of the screw head provides a slight mechanical advantage for applying torque against the screw. Wider screw heads and screwdriver blades generally require less torque exertion at the screwdriver shaft.

We ignore frictional force by assuming that friction between the screw and screwdriver blade is zero. (Because in this case, friction assists the operator by helping keep the screwdriver blade in the screw slot, zero friction would be the worst-case condition.) If the width of the screwdriver blade is w and the applied torque at the screwdriver shaft is T , then the normal contact force, F_C , between the blade and the screw head slot is

$$F_C = \frac{T}{W}$$

Because the blades of slotted screwdrivers are usually tapered to an angle ϕ to ease insertion of the screwdriver blade and accommodate different size screw slots, the normal contact force F_C is not actually perpendicular to the screwdriver shaft but rather acts at an angle perpendicular to the blade edge (Fig. 6e.4). This results in an axial force at each contact point

$$F_y = F_C \sin \phi = \frac{T}{W} \sin \phi$$

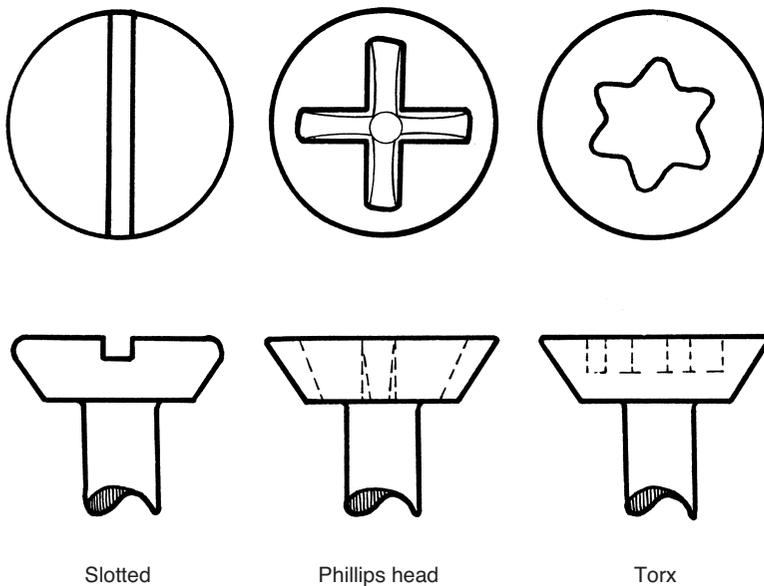


Figure 6e.3 Slotted head, Phillips head, and Torx™ head screws.

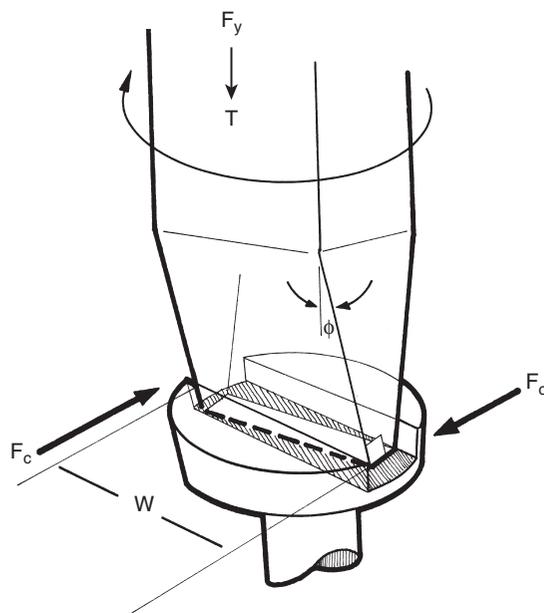


Figure 6e.4 Static forces acting on a slotted screwdriver blade and shaft.

that acts to push the screwdriver blade out of the slot as torque is applied to the shaft. The hand must react against this force by exerting an equal and opposite axial force F_y that is a component of the feed force. Because there are two contact points, the total axial force is $2F_y$. Consequently, the axial force required to keep the blade from coming out of the slot is

$$F = 2F_y = 2 \frac{T}{W} \sin \phi.$$

The greater the torque T , the greater the axial force needed to keep the screwdriver blade in the slot. If the screwdriver blade taper angle ϕ is 12 degrees,

$$F = 2 \frac{T}{W} \sin(12^\circ) = 0.42 \frac{T}{W}.$$

If the screwdriver blade angle is not tapered but parallel to the slot, this force is negligible ($F_y = 0$) because no axial force acts to unseat the blade. Such a screwdriver, however, would be limited to certain size slots and more difficult to insert into them.

Phillips head screws

Although slotted screws are simpler, screwdriver blades sometimes slip out of slotted heads and have the potential to damage or scratch the work piece. The Phillips head screw (Fig. 6e.3) gained popularity because it prevented slippage and discouraged vandals from removing screws in public places with a coin or knife edge.³¹

A Phillips head screwdriver blade contains four wedges acting on the blade. Similarly to the slotted screwdriver, the axial forces acting parallel to the fastener can be described by the equation

$$F = 4F_y = 4F_c \sin \phi = 4 \frac{T}{W} \sin \phi.$$

Because ϕ is typically greater for Phillips head screws and w is much smaller, F_y is considerably more than for slotted screwdrivers. The typical taper angle for a Phillips head screw is $\phi = 40$ degrees, so

$$F = 4 \frac{T}{W} \sin(40^\circ) = 2.57 \frac{T}{W}.$$

which is more than six times the force needed for a slotted screw with an equivalent diameter head.

Torx™ head screws

Torx™ screws offer the advantages of *both* slotted screws and Phillips head screws. Because $\phi = 0$ for Torx™ head screws (Fig. 6e.3), no axial force component other than the actual feed force is required to advance the fastener. Because the screwdriver blade cannot be tapered to accommodate different-size screws, Torx™ head screws are not as flexible as slotted or Phillips head screws. The disadvantage of requiring a large assortment of screwdrivers with corresponding blade sizes may be outweighed by the mechanical advantage of Torx™ head screws. Furthermore, they are more difficult to tamper with because Torx™ head screwdrivers are less readily available than slotted and Phillips head screwdrivers and an assortment of sizes are needed. The advantages and disadvantages of slotted, Phillips, and Torx™ head screws are summarized in Table 6e.1.

PLIERS AND CUTTING TOOLS

The particular finger or combination of fingers used can affect grip strength.^{2,37} As the strongest fingers, the thumb, index, and middle fingers should be used for producing the most grip force. The weaker ring and small fingers should be used for stabilizing handles rather than acting as primary force contributors. Sometimes tool operators handle tools in ways that take these differences into account.

Table 6e.1 Summary of ergonomic advantages and disadvantages of different screw heads

Screw head	Advantages	Disadvantages
Slotted	Very flexible tool—one size fits all Requires little axial feed force	Difficult to keep seated in the slot Can slip and damage work piece
Phillips	Easy to keep seated in head Flexible tool	Requires more axial feed force
Torx™	No axial feed force needed Easy to keep seated in head	Inflexible—must have a specific size for an associated screw head

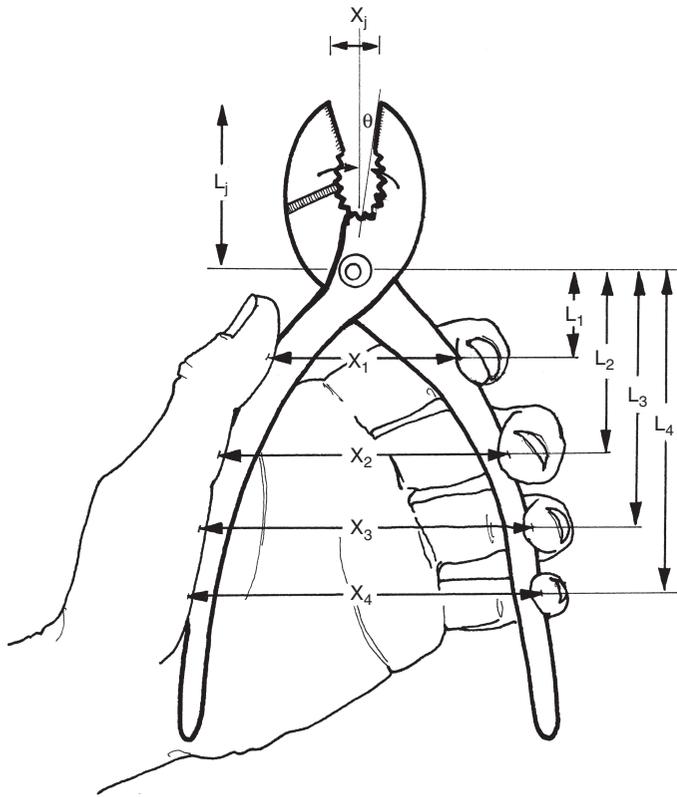


Figure 6e.5 Static forces acting on the hand when a pair of pliers is grasped.

Offering the mechanical advantage provided from squeezing together two opposing lever arms, pliers are used often for pinching, grasping, and cutting. The common use of pliers involves a grip depicted in Figure 6e.5, where the pliers jaw is held on the radial side of the hand. In many instances, however, this grip does not optimize the mechanical advantage with finger strength and can result in greater exertion than necessary.

Swedish researchers observed that some sheet metal workers held metal shear blades on the ulnar side of the hand by using an inverted grip (Fig. 6e.6) rather than that used with conventional shears.^{10,41} Finger strength data revealed that the inverted grip allowed a greater span between the larger index finger and thumb than between the small finger and the palm, providing a better-suited handle size for more force in each cut.¹⁴

The articulation angle from the closed position to the pivot point is defined as θ . The jaw span X_j is related to the grip span X_i as

$$X_i = X_j \frac{L_i}{L_j}$$

where L_i is the distance from the fulcrum to the finger i , L_j is the distance from the fulcrum to the jaw tip, and X_i is the grip span available for finger i .

Assuming there are no coupling effects between fingers, the resultant force is the sum of all four fingers. Individual-finger

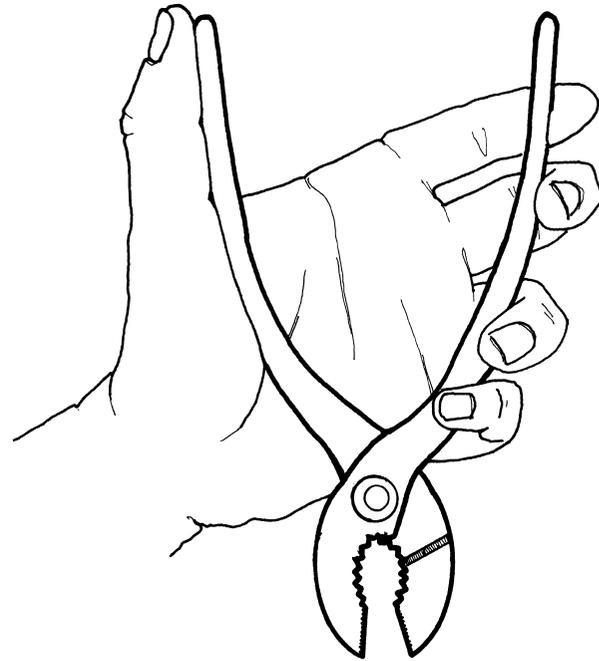


Figure 6e.6 Inverted pliers grip.

normal strengths for the distal phalanx while grasping handles of different sizes are taken from Amis.² By summing the moments about the pivot point, the total moment is

$$M_j = F_1 L_1 + F_2 L_2 + F_3 L_3 + F_4 L_4$$

This moment is counteracted by that produced from reaction forces at the jaw. Consequently, the maximum jaw force is

$$F_j = \frac{M_j}{L_j}$$

Using the dimensions provided in Table 6e.2, the maximum jaw force available increases from 714 to 786 N (10) just by inverting the handle. Because the index and middle fingers have the greatest strength, they are provided with larger moment arms for generating force with the inverted grip, providing additional mechanical advantage. One study observed that the maximum force of one finger depended not only on its grip span but also on those of the other fingers.¹⁴

POWER HAND TOOLS

One of the best methods of controlling applied hand exertion is to substitute a power hand tool for a manual tool. In fact, many repetitive jobs could not be performed without the use of power tools. Modern power hand tools can operate at high speeds and produce very high forces. Exertions and forces acting against the hand in power tool operation can be reduced by eliminating excess weight, by making the best use of the mechanical advantage, or by

Table 6e.2 Pliers handle dimensions and associated finger strength for showing the mechanical advantage using an inverted grip

Grip	Index	Middle	Ring	Small	Total
Conventional					
Grip span X_i (cm)	6.0	6.6	6.4	5.4	
Grip strength F_i (N)	60	63	44	37	204
Finger distance L_i (cm)	7.0	8.3	10.2	11.4	
Torque (Nm)	420	523	449	422	1814
Jaw force F_j	165	206	177	166	714
Inverted					
Grip span X_i (cm)	5.4	6.4	6.6	6.0	
Grip strength F_i (N)	62	64	43	35	204
Finger distance L_i (cm)	11.4	10.7	8.3	7.0	
Torque (Nm)	707	685	357	245	1994
Jaw force F_j	278	270	141	97	786

providing mechanical aids for holding tools, parts, and materials. Selecting a power hand tool having certain dimensions and shapes can often reduce tool reaction forces and provide mechanical advantages that assist the operator. Increasing friction between the hand and objects grasped can also reduce the forces required for gripping tools.

Nut runners and power screwdrivers are widely used for securing screws and threaded fasteners in manufacturing and assembly operations, such as in the automotive, mechanical equipment, and electronics industries. Using electromyography as an index of muscle effort during pneumatic shut-off nut-runner operation, Radwin et al³⁷ observed that electromyographic activity during threaded fastener torque buildup was affected by tool torque output and torque buildup time. Electromyographic activity during torque buildup was more than three times greater than during preparation and shut-off.

Oh and Radwin²⁹ observed that the operator initially overcomes the tool reaction force with a concentric muscle exertion. As the force rapidly rises, the tool eventually overcomes the operator, causing the motion in opposition to muscle contraction and resulting in an eccentric muscle exertion. Due to passive properties of the muscle, during an eccentric, or lengthening, contraction the muscle acts like a spring, producing proportionally more force as it lengthens.

Because they directly affect handle force in a complex manner, tool geometry, mass, moment of inertia, and center of gravity are important factors in the design and selection of power hand tools. By providing mechanical advantages, the handle length of pistol-grip and right-angle tools and the diameter of in-line tool handles likewise affect hand exertions.^{11,20,36} Tool load affects grip force,^{9,16,21,43} fatigue onset,¹⁸ task performance,¹³ and subjective preference by tool operators.^{3,30,42} In addition to the static forces exerted by an operator when carrying and positioning tools or when a tool is running at a constant state, the impulsive forces and torques produced by rotating spindle power hand tools are dynamic.

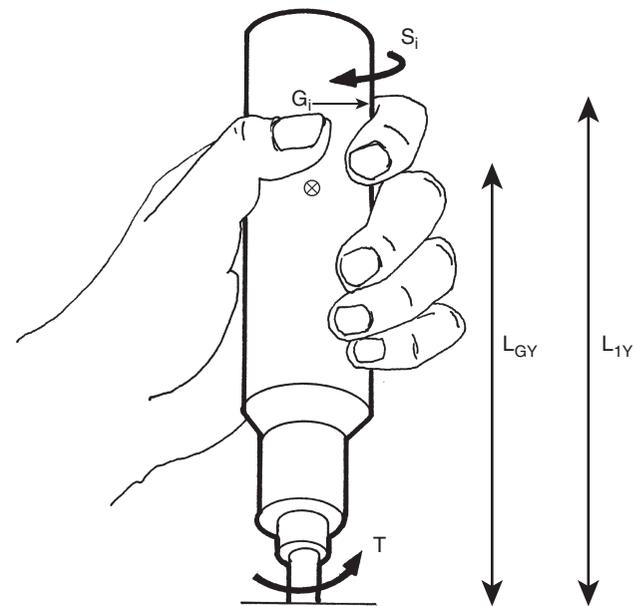


Figure 6e.7 Forces acting in the hand when an in-line nut runner is operated.

Static forces

Lin et al²² developed a mechanical model of power hand nut-runner operation for static equilibrium (no movement) conditions. Using hand force, reaction force from the work piece, tool weight, and tool torque, the static force model calculates handle force when carrying tools and when spindle torque is constant.

The model uses a Cartesian coordinate system relative to the orientation of the handle grasped using a power grip (Fig. 6e.7A). This coordinate system has the x -axis perpendicular to the axial direction of the handle, the y -axis passed through the long axis of the handle, and the z -axis perpendicular to both. The origin is the end of the bit or socket.

Hand forces are described here in relation to these coordinate axes. To simplify the model, we assume that orthogonal forces can be summed along the handle without producing coupling moments, an assumption that allows force to have a single point of application. The variables used in the model are summarized in Table 6e.3 and illustrated in Figure 6e.7.

When a tool is in static equilibrium, the sums of all forces (F), moments (M) about the origin, and grip moments generated by the spindle (M_G) are zero. Therefore three vector equations can be developed:

$$\Sigma F_i + \Sigma R_i + W + F_F + F_s = 0 \quad (\Sigma F = 0)$$

$$\Sigma (F_i + R_i) \times L_i + W \times L_G = 0 \quad (\Sigma M = 0)$$

$$\Sigma S_i \times G_i + T = 0 \quad (\Sigma M_G = 0)$$

These vector equations can be written in matrix form:

The full model considers forces and moments exerted by both hands (subscripts 1 and 2), but not all these equations are

$$\begin{bmatrix}
 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
 0 & L_{1z} & -L_{1y} & 0 & L_{2z} & -L_{2y} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 -L_{1z} & 0 & L_{1x} & -L_{2z} & 0 & L_{2x} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 L_{1y} & -L_{1x} & 0 & L_{2y} & -L_{2x} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & G_{1x} & 0 & 0 & G_{2x} & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & G_{1y} & 0 & 0 & G_{2y} & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & G_{1z} & 0 & 0 & G_{2z} & 0 & 0 & 0 & 0
 \end{bmatrix} \times$$

$$\begin{bmatrix}
 F_{1x} \\
 F_{1y} \\
 F_{1z} \\
 F_{2x} \\
 F_{2y} \\
 F_{2z} \\
 S_{1x} \\
 S_{1y} \\
 S_{1z} \\
 S_{2x} \\
 S_{2y} \\
 S_{2z} \\
 F_{sx} \\
 F_{sy} \\
 F_{sz}
 \end{bmatrix} = \begin{bmatrix}
 -W_x - R_{1x} - R_{2x} - F_{Fx} \\
 -W_y - R_{1y} - R_{2y} - F_{Fy} \\
 -W_z - R_{1z} - R_{2z} - F_{Fz} \\
 L_{1z}R_{1y} - L_{1y}R_{1z} + L_{2z}R_{2y} - L_{2y}R_{2z} - L_{Gz}W_y + L_{Gy}W_z \\
 L_{1x}R_{1z} - L_{1z}R_{1x} + L_{2x}R_{2z} - L_{2z}R_{2x} - L_{Gx}W_z + L_{Gz}W_x \\
 L_{1y}R_{1x} - L_{1x}R_{1y} + L_{2y}R_{2x} - L_{2x}R_{2y} - L_{Gy}W_x + L_{Gx}W_y \\
 -T_x \\
 -T_y \\
 -T_z
 \end{bmatrix}$$

required for all situations, and in certain cases the equations system may be reduced depending on tool shape and operating conditions. For example, the shear force needed for in-line tools is insignificant for pistol grip tools except when a hand grasps the tool around the spindle. The tool torque and feed force are

assumed always to act in a single axis. When the matrix becomes degenerate or singular, additional assumptions are needed to solve for handle force.

Nut runners are commonly configured as pistol grip, right angle, and in-line (Fig. 6e.7). Examples are provided in this article to demonstrate the resulting matrix reduction for these three common tool shapes. A set of more general cases are fully described in Lin et al.²²

Table 6e.3 Legend of variable notation

Variable*	Description
F_i	Handle force acting on hand <i>i</i>
S_i	Shear force acting in hand <i>i</i> , applied when the handle rotates in the <i>y</i> -axis
R_i	Reaction force produced by the spindle torque at point <i>i</i>
W	Tool weight
F_F	Feed force; not applicable when carrying a tool
F_s	Surface support force; not applicable when carrying a tool
T	Tool torque
L_i	Location vector of point <i>i</i>
L_G	Location vector of the center of gravity
G_i	Grip radius at point <i>i</i> , applied when the handle rotates in the <i>y</i> -axis

*All the variables in bold type are vectors. Subscript *i* represents a specific hand used in operating the tool. The right hand is annotated using subscript 1 and the left hand is annotated using subscript 2.

Pistol-grip power drivers

Consider the free-body diagram of the pistol-grip nut runner in Figure 6e.7B, which shows the use of the right hand (subscript 1), and the tool geometry shown in Figure 6e.8A. The spindle stall torque *T* acts clockwise in the *xy*-plane. The tool operator must oppose this equal and opposite reaction torque *T_z* counterclockwise by producing a reaction force *R_{1x}* along the *x*-axis that is equal to and opposite of the hand force component *F_{1x}*.

This is not, however, the only force that the tool operator must produce. A force acting along the *z*-axis *F_{1z}* provides feed force *F_{Fz}* and produces an equal and opposite reaction force *F_{Sz}*. The operator must also react against the tool mass to support and position the tool by producing a vertical force component *F_{1y}*. The tool weight *W_y* and push force *F_{1z}* tend to produce a clockwise rotation of the power tool about the spindle in the *yz*-plane that is countered by this vertical support force.

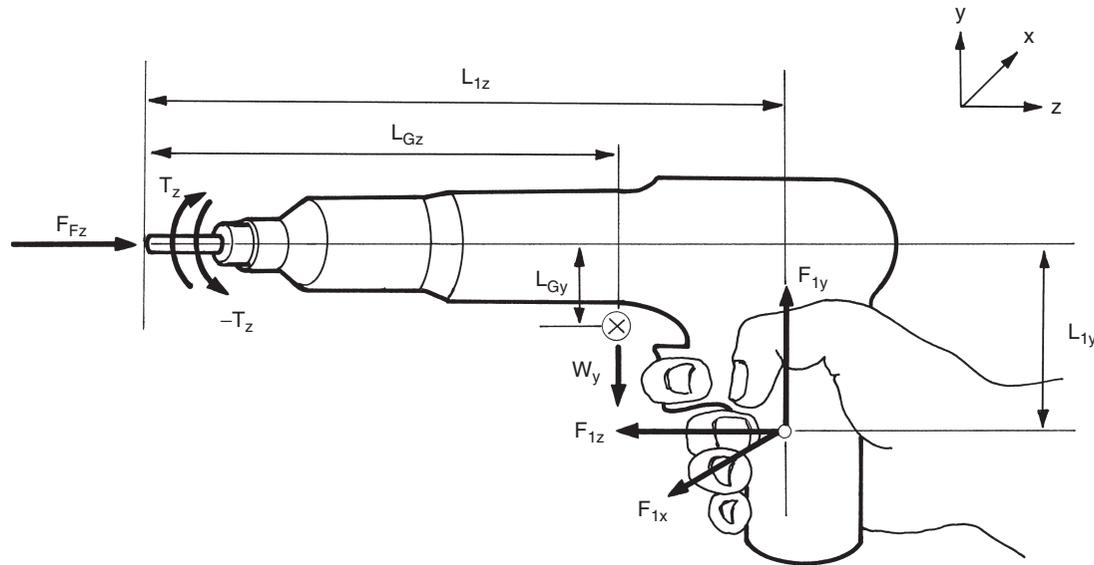


Figure 6e.8 Static forces during pistol-grip nut runner operation.

In the case of one-handed operation, the right hand (subscript 1) reacts against all tool forces and torques. The vector equations can therefore be reduced to

$$\begin{bmatrix} 0 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & L_{Lz} & -L_{Ly} & 0 & 0 \\ L_{Ly} & 0 & 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} F_{1x} \\ F_{1y} \\ F_{1z} \\ F_{sy} \\ F_{sz} \end{bmatrix} = \begin{bmatrix} 0 \\ -W_y \\ -F_{Fz} \\ -W_y L_{Gz} \\ -T_z \end{bmatrix}$$

These equations reveal several relationships between tool parameters and hand force. Torque reaction force $R_{1x} = F_{1x}$ is directly proportional to the reaction torque T_z and inversely proportional to the handle length L_{Ly} . The torque reaction force is therefore less for longer tool handles than for shorter handles. The vertical support force F_{1y} is inversely proportional to the tool length L_{Lz} and dependent on tool weight, center of gravity location, handle length L_{Ly} , and feed force $F_F = F_{1z}$. The equations indicate that less effort is probably needed for supporting a pistol-grip power hand tool when the tool body is long than when it is short. When feed force is large, supporting force decreases when the handle length is short.

This is why handles aligned close to the tool spindle axis and with long tool bodies are advantageous for tools such as power hand drills. These drills often require considerable feed force with torque reaction forces relatively less than for a nut runner, so a short handle is favorable. Alternatively, when torque is large and feed force is small, a tool with a long handle is advantageous. When both feed force and torque are significant factors, however, as when drilling large holes or shooting self-tapping screws in hard wood, these parameters must be optimized.

The model can be used for comparing resultant hand forces associated with different tools for the same operation and for

selecting the tool requiring the least exertion. Consider the four hypothetical power nut runners shown in Figure 6e.9. All four tools weigh the same (30 N) and have the same torque output with different dimensions and mass distribution. Comparisons between the four tool dimensions are provided in Table 6e.4.

Assuming one-handed operation, resultant hand force was predicted by using the model for the four different tools and plotted as a function of torque in Figure 6e.9. Hand force was determined for both low-feed force (1 N) and high-feed force (100 N) conditions when the tools were operated against a vertical surface. When feed force was small, the resultant hand force was affected mostly by the torque reaction force, which increased as torque increased for all four tools. Because the greatest force component in this case was the torque reaction force, tools 3 and 4 resulted in the least resultant hand force because they had the longest handles (Table 6e.4). Tool 3, however, had a considerably greater resultant hand force when feed force was high because the hand was located farthest from the spindle for that tool. This effect was not observed for tool 4, which also had a long handle, because of its greater tool body length. Although tool 4 had the least resultant hand force when both feed force and torque levels were high, tools 1 and 2 had less resultant hand force for high feed force and low torque because these tools permitted the hands to grasp the tool close to the spindle axis. Consequently, the best tool depended on both feed force and the torque requirements for the task.

All tools were assumed to weigh the same; had they varied weights, the differences might have been even greater. Additional factors the model can consider include relative tool weight, mass distribution, and tool orientation. This analysis does not take into account the relative strength capabilities of the hand in the three component directions, although use of such a model does not exclude strength comparisons.

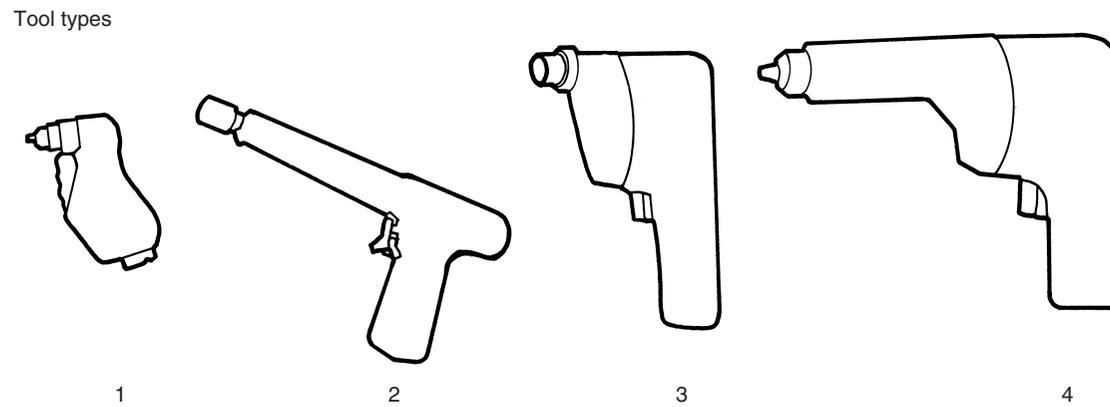


Figure 6e.9 Comparison of resultant hand forces acting on the hand for four equivalent power nut runners plotted against reaction torque.

The reaction force transmitted to the hand for right-angle power drivers is affected also by the magnitude of spindle torque and the tool dimensions. Right-angle nut runner spindle torque can range from less than 0.8 Nm to more than 700 Nm. A tool operator opposes these forces while supporting the tool and maintaining control. This torque is transmitted to the operator as a reaction force and opposed by the great mechanical advantage resulting from the long reaction arm created by the tool handle.³⁷

Right-angle power drivers

A right-angle nut runner is functionally nothing more than a pistol-grip nut runner with a very short body and long handle. The model for a right-angle nut runner is shown in Figure 6e.7C. Because right-angle nut runners are usually operated with both hands, two-hand forces are now in the z -axis; F_{1z} is applied at the handle for supporting the tool, and F_{2z} is applied over the tool spindle to help provide feed force. (When these tools are used one handed, the equations for a pistol grip nut runner apply.)

Right-angle tools have short spindles perpendicular to the long axes of the handles. Because the handle is usually longer than the spindle, these tools are often held in two hands (Fig. 6e.7C). In this case, the right hand (subscript 1) grasps the tool at the distal end of the tool handle, whereas the left hand (subscript 2) grasps it proximal to the spindle. It is further assumed that equal amounts of force are exerted by both hands to react against tool torque along the long axis of the handle, and hence $F_{1z} = F_{2z}$. The resulting matrix is

$$\begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & -1 \\ 0 & L_{1y} & 0 & L_{2y} \\ L_{1y} & 0 & L_{2y} & 0 \end{bmatrix} \times \begin{bmatrix} F_{1x} \\ F_{1z} \\ F_{2x} \\ F_{2z} \end{bmatrix} = \begin{bmatrix} -W_x \\ 0 \\ -T_x \\ -W_x L G_y \end{bmatrix}$$

These equations can be used to compare hand forces between a right-angle and a pistol-grip power nut runner used on a horizontal surface (Fig. 6e.10). The right-angle nut runner in this example weighs 20 N, whereas the pistol-grip nut runner weighs 50 N. A graph of torque reaction force plotted against torque shows that the mechanical advantage of the right-angle nut runner for high torque levels is considerable. The other hand, however, exerts greater feed force for the right-angle nut runner than for the pistol-grip nut runner. Because the pistol-grip nut runner weighs more and has its center of gravity closer to the tool spindle, it requires less support force for F_{1z} and F_{2z} than for the right-angle nut runner (Fig. 6e.10). Sometimes handle force can be reduced further through the proper use of accessory handles and torque reaction arms.

In-line power drivers

The form factor and associated forces and moments involved in operating an in-line power tool are shown in Figure 6e.7D and dimensions in Figure 6e.8C. Assuming that the right hand (subscript 1) supports the tool, the static handle force matrix is

$$\begin{bmatrix} 1 & 0 \\ 0 & G_{1x} \end{bmatrix} \times \begin{bmatrix} F_{1y} \\ S_{1y} \end{bmatrix} = \begin{bmatrix} -W_y \\ -T_y \end{bmatrix}$$

The static torque developed at an in-line power hand tool spindle has an equal and opposite reaction torque T_y that must be overcome by tangential shear forces between the hand and the handle. The tangential shear force S_{1y} produces torque about the grip radius G . The shear force S_{1y} is proportional to the compressive hand force F_G and the coefficient of friction μ between the hand and the handle, similar to a manual screwdriver except in this case the spindle rather than the hand is producing the torque. In-line power driver operation is therefore limited by the

Table 6e.4 Pistol-grip nut runner dimensions, load, and center of gravity location

Tool	Weight (N)	L_{1z} (m)	L_{1y} (m)	L_{1z} (m)
1	30	0.09	0.06	0.07
2	30	0.40	0.09	0.26
3	30	0.11	0.50	0.07
4	30	0.40	0.50	0.32

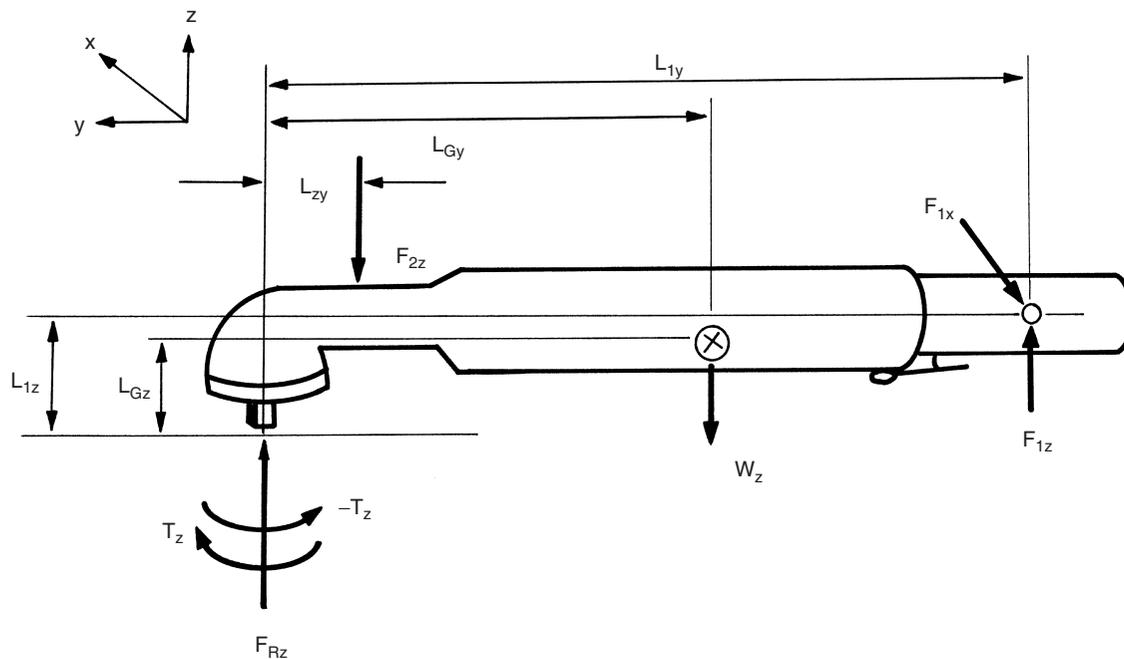


Figure 6e.10 Static forces for right-angle nut runner operation.

maximum compressive grip force an operator can produce and by the dimensions of the tool. The relationship between the static torque, grip force, and tool diameter is similar to that of manual screwdriver operation:

$$T_y = S_{1y}G = \mu F_G G$$

Push-to-start activated power hand tools free the operator from having to squeeze a trigger or lever, but they can increase force requirements because they require more feed force to start them. A flange at the end of in-line handles helps prevent the hand from slipping during feed force exertion.¹⁵

Accessory handles and torque reaction arms

Accessory handles assist a pistol-grip power tool operator by providing an additional handle for two-handed operation. A torque reaction bar can sometimes be used to transfer loads back to the work piece. In fact, reaction torque can be completely eliminated from the operator's hand by use of either a stationary reaction bar adapted to a specific operation so that reaction force can be absorbed by a convenient solid object or a torque-absorbing suspension system.

A reaction bar can be installed on in-line, pistol-grip, and angled tools. The advantages of tool-mounted reaction devices are that (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 nut runners, 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 nut runners in most tool sizes; and (5) use of reaction bars can improve tool performance.

The limitations are that (1) torque reaction bars must be custom-made for each operation, (2) several attachments can make tool use difficult, (3) adding weight to the tool makes it more cumbersome to handle, and (4) the intervention is not practical when the accessibility is limited, the manipulation is restricted, or the reaction bar has no surfaces to contact. If a reaction bar is provided, however, a smaller tool handle can be used.

When an accessory handle or torque reaction bar is used with a pistol-grip nut runner (Fig. 6e.11), the horizontal hand force F_{1x} is reduced. If a vertical force is applied to a torque reaction bar, as depicted in Figure 6e.12, an additional term is needed for the sum of the moments in the z-axis:

$$T - F_{1x} L_{1y} + F_{Sy} L_{Sx} = 0$$

As a result, F_{1x} becomes

$$F_{1x} = -F_{Sy} L_{Sx} + \frac{T}{L_{1y}}$$

If a torque reaction bar is used and all the torque reaction force acts against a stationary object, then

$$T = -F_{Sy} L_{Sx}$$

Consequently,

$$F_{1x} = 0$$

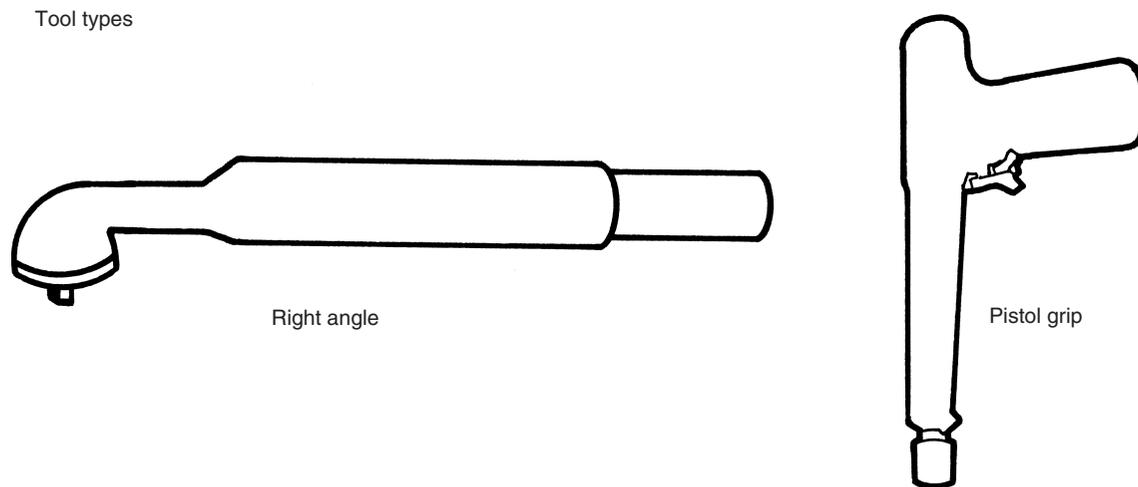


Figure 6.11 Comparison of hand forces between a right-angle nut runner and a pistol-grip nut runner operated on a horizontal surface.

Tool counterbalancers

The force requirements for a job are often related to the weight of the tools being handled. The effort needed for holding an object in the hands is usually associated with its mass,^{34,35} so that heavier tools generally require greater exertion. There is a trade-off between the selection of a lightweight tool and the benefit of the added weight for performing operations that require high feed force. A spring counterbalance or air balancer can help reduce the load from heavy tools that are operated frequently.

When used to support the tool, the counterbalance produces a force that opposes gravitational force. This is illustrated with a pistol-grip power tool in Figure 6.13. When the tool is held freely in the hand, there is no torque to react against ($T = 0$) and consequently no reaction force ($F_{1x} = 0$). Besides creating a

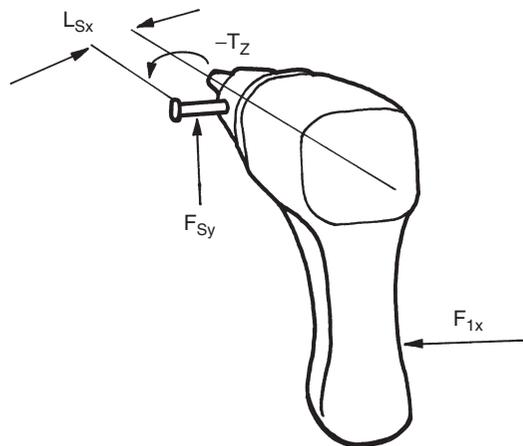


Figure 6.12 Force and moment arm for a pistol-grip nut runner equipped with a torque reaction bar.

moment in the yz -plane, the counterbalance force F_{Cy} also influences F_{1y} . The moment is counteracted by a coupling moment, C , from the hand, as described in the following equations:

$$F_{1y} + W_y + F_{Cy} = 0$$

$$F_{1y}L_{1z} + W_yL_{Gz} + F_{Cy}L_{Cz} + C = 0$$

If the counterbalance force F_{Cy} is set to counteract the tool weight W_y , then

$$F_{Cy} = -W_y$$

Consequently, the y -axis component of the hand force becomes $F_{1y} = 0$. The location that the counterbalance force acts against the tool can affect operator exertion when holding it. Solving for the coupling moment C ,

$$C = F_{Cy}(L_{Gz} - L_{Cz})$$

The equation shows that the coupling moment can be eliminated ($C = 0$), if

$$L_{Gz} = L_{Cz}$$

Balancers should therefore be attached to tools at or near their centers of gravity so as to avoid additional effort by the tool operator to counteract the handle moment.

Balancers should be installed carefully 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 force so the tool weight is reduced. If installed incorrectly, however, these balancers can actually have the reverse effect of increasing force. Spring tension should be adjusted so that the operator does not have to counter more force than necessary and balancers so that the tool aligns as close 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 must elevate the shoulder to reach it; the tool should remain suspended at the same height at

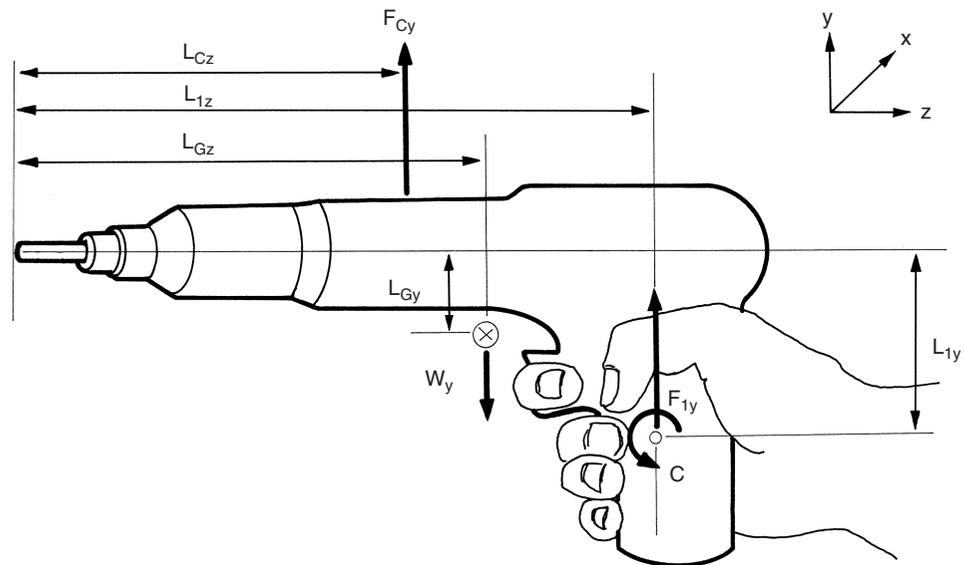


Figure 6e.13 Static forces when handling a pistol-grip power hand tool with a counterbalance. Counterbalance force F_{Cy} creates a moment in the yz -plane that is counteracted by a coupling moment C .

which it was released. Also, situations where operators tend to work ahead of or behind the assembly line should be avoided. If a tool is moved horizontally, a trolley and rail system should be installed. Special attention may be required to be sure that the balancer is attached directly above the work.

Dynamic forces

Tool torque buildup model

There are three elements involved in power nut runner operation using a threaded fastener: the operator, the tool, and the mechanical joint that joins or clamps two objects together, the hardness of which is analogous to the stiffness of a spring. The clamping

force of a threaded fastener is therefore proportional to torque, with a desired clamping force achieved by rotating the fastener to a specific target torque. Levels of joint stiffness range from a hard joint (30 degrees of spindle rotation) to a soft joint (360 degrees of spindle rotation). Examples are illustrated in Figure 6e.14

The spindle torque and angular displacement during torque buildup have a linear relationship such that

$$\theta(T) = \frac{\theta_t}{T_t - T_0} (T - T_0)$$

where T is tool spindle torque, θ is spindle angular displacement, T_t is the target torque, T_0 is the rundown torque, and θ_t is the target angle.

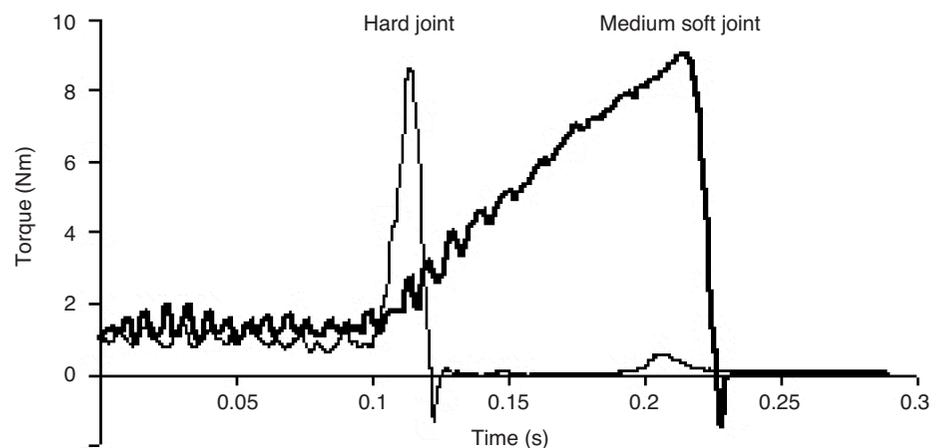


Figure 6e.14 Recording of torque buildup profiles for hard (*light line*) and medium-soft (*heavy line*) joints. (From Lin JH, Radwin RG, Fronczak FJ, Richard TG: *Ergonomics* 46(12): 1161-1177, 2003.)

Pneumatic motors have a distinctive speed-torque relationship. The motor does not produce torque at the free running speed, whereas it exerts maximum torque when the motor stalls. The spindle speed can be described using the equation

$$S(T) = S_0 \left(1 - \frac{T}{T_{\max}}\right),$$

where S is spindle speed expressed as a function of torque T , T_{\max} is the motor maximum torque output, and S_0 is free running speed.

Because speed $S(T)$ is the derivative of angular displacement $\theta(T)$, the unique solution for the differential equation is the torque delivered to the spindle

$$T(t) = T_{\max} + (-T_{\max} + T_0) e^{-\frac{(T_0 - T_{\max})S_0}{\theta_0 T_{\max}} t}$$

The force experienced by the hand can be obtained by dividing the equation for $T(t)$ by the distance of the hand from the rotating spindle.

Handle force model: dynamics

Lindqvist²⁵ proposed that a simple mass-spring mechanical system might be sufficient to describe the handle response to impulsive reaction forces encountered in nut runner operation but did not identify specific parameters for these elements. Lin et al²³ advanced this model of the human operator; their method identifies these mechanical properties to predict the kinematic and kinetic response of the handle (motion and force) when an impulsive reaction force was encountered in threaded fastener power hand tool operation. A brief description of the model is provided here.

The human operator is represented as a dynamic mechanical analog of a single degree-of-freedom mechanical system consisting of a linear spring, a mass, and a viscous damper (Fig. 6e.15). Instead of modeling for individual contributing muscles, the model combines the loading of the muscles and joints into mechanical elements without considering the directions of the loads. The mechanical properties, M_s , k_s , and c_s , are assumed to be passive and invariant for an individual, a given posture, and a tool orientation. The effective mass M_s represents the total contributions of the standing operator coupled to the tool through the hands. The effective spring stiffness and damping represent the gross effect of the operator acting against the handle, including contributions from the entire body and nonspecific muscle groups. A system identification method using free oscillation measures these mechanical parameters for various work locations for three common tool shapes: pistol grip, right angle, and in-line. This method measures the influence of the operators' mechanical elements on the system dynamic response (oscillation frequency and damping ratio) of a known mechanical system. The mechanical parameters are then extracted analytically.²³

Given the mechanical parameters for an operator, the model estimates the dynamic response (angular displacement and force) when the operator encounters an impulsive reaction force from a power tool. A torsional dynamic equilibrium equation about the tool spindle axis can be written. The

following differential equation results in terms of the tool rotation θ :

$$(J_T + M_s h^2) \frac{d^2 \theta}{dt^2} + c_s h^2 \frac{d\theta}{dt} + k_s h^2 \theta = T(t)$$

where $T(t)$ is the tool torque, M_s , c_s , and k_s are the operator mechanical parameters, J_T is the mass moment of inertia of the tool about its spindle, and h is the distance between the hand and the tool spindle.

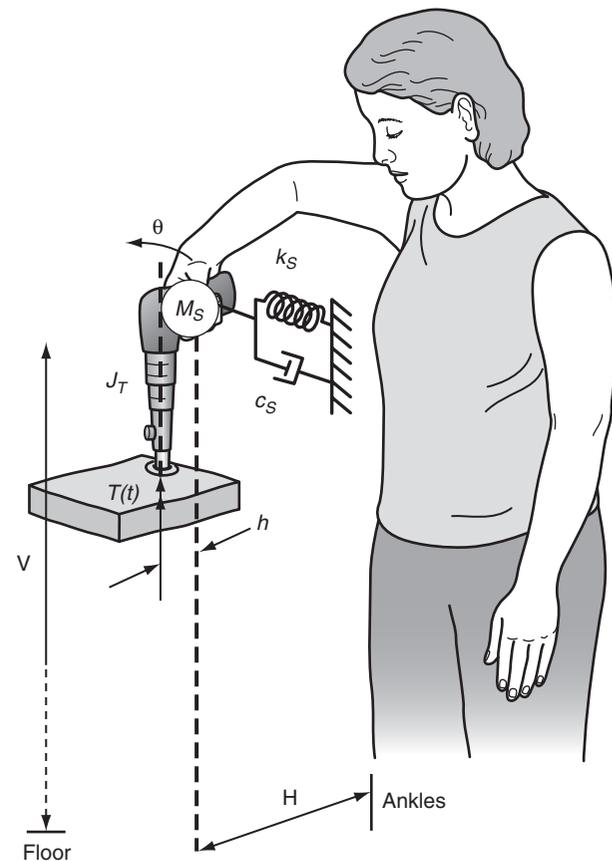


Figure 6e.15 A pistol-grip pneumatic hand tool is illustrated with a normal operator grip. The mechanical parameters can be defined as follows: M_s = the total effective mass of the operator's arm, hand, and a portion of the upper body lumped at the distance h from the center of rotation of the tool spindle or line of action of the tool torque, $T(t)$. J_T = the rotational mass moment of inertia of the tool about the center of mass of the tool. h = location of the center of pressure of the operator's hand on the tool handle. k_s = the effective stiffness of the operator's arm, hand, and a portion of the upper body. c_s = the effective damping of the operator's arm, hand, and a portion of the upper body. $T(t)$ = the tool torque which is transmitted to the operator in a typical mechanical fastening operation. θ = the rotation of the tool and hand about the tool spindle axis. H = horizontal distance between the floor and the handgrip. V = vertical distance between the ankles and the handgrip. (From Lin JH, Radwin RG, Richard TG: Handle dynamics predictions for selected power hand tool applications. *Hum Fact* 45(4):645-656, 2003.)

This second-order differential equation can be solved numerically using finite difference techniques and a discrete time step variation of the tool torque, $T(t)$. The result will be a description of the time variation of the tool rotation, $\theta(t)$,

$$\theta_{i+1} = \left\{ \frac{1}{\frac{Msh^2 + J_T}{(\Delta t)^2} + \frac{csh^2}{2\Delta t}} \right\} \left[\left\{ \frac{2(Msh^2 + J_T)}{(\Delta t)^2} - ksh^2 \right\} \theta_i + \left\{ \frac{csh^2}{2\Delta t} \frac{2(Msh^2 + J_T)}{(\Delta t)^2} \right\} \theta_{i-1} + T_i \right],$$

where i is the iteration step, Δt is the time step, and T is the tool torque.

With the rotational response of the tool predicted, the motion of the handle can be defined as $h\theta(t)$. The force $F(t)$ delivered to the handle can be approximated by

$$csh \frac{d\theta}{dt} + ksh\theta = F(t)$$

Here the handle force F was estimated by solving the above equation. The tool operator mechanical model was also used to estimate tool handle kinematics during torque buildup. The resultant handle displacement and force for using a right-angle tool having buildup times ranging from 35 (hard) to 1000 (soft) ms was calculated and is plotted in Figure 6e.16 for the female with the smallest stiffness and the male with the greatest stiffness.²⁴

CONCLUSIONS AND RECOMMENDATIONS

Tool operator exertion can be minimized by considering the forces acting on the tools and the way they are used for a specific task. The selection of alternative hand tools for different work

situations can be assisted by comparing the mechanical relationships between the task and tool parameters. Other aspects that should be considered but are not covered in this chapter include repetitive use, assumed postures, vibration exposure, and contact stress.

The following recommendations can be made:

1. When large feed forces are necessary, use the longest manual screwdriver available and provide a screwdriver shaft long enough so that it can be gripped by the other hand as a guide. Nut drivers and socket drivers also help reduce hand forces by providing concentric handle rotation and additional mechanical advantage at the screw head.
2. Large-diameter manual screwdriver handles with high frictional characteristics are recommended; if the handle diameter is too large, however, the mechanical advantage may be counteracted by reduced grip strength.
3. Phillips head screws should be avoided because they require greater axial push force as torque increases. Torx™ head screws provide the least axial reaction force.
4. Pliers and shears can sometimes be used to a greater mechanical advantage by gripping them so that the pivot is on the ulnar rather than the radial side of the hand.
5. Torque reaction force is less for longer pistol-grip and right-angle nut runners than for equivalent tools with shorter handles.
6. When pistol-grip power hand tools that have longer tool bodies are used, less vertical support force is required than for

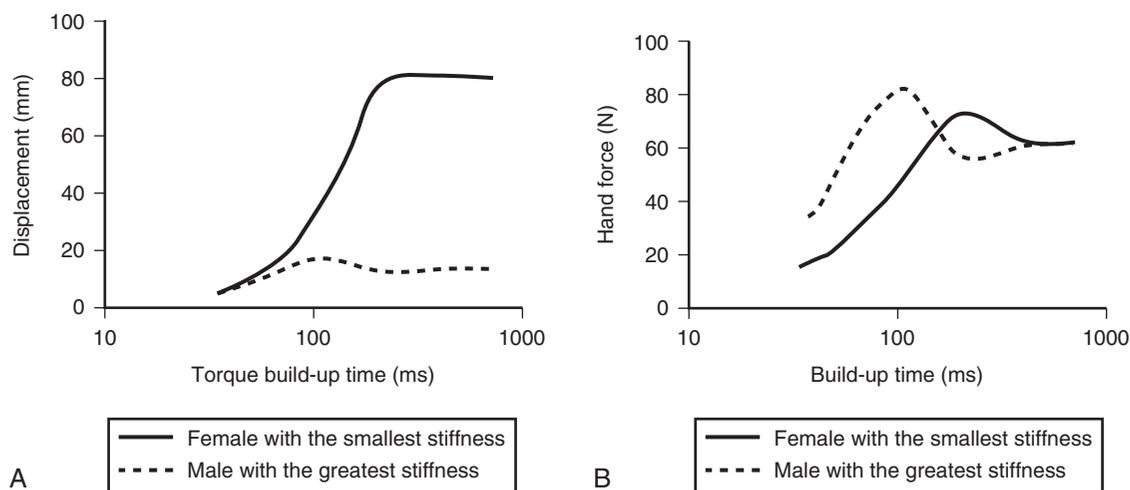


Figure 6e.16 Model prediction for handle displacement and force when using a right-angle nut runner on a horizontal surface for different torque buildup times. (From Lin JH, Radwin RG, Richard TG: Handle dynamics predictions for selected power hand tool applications. *Hum Fact* 45(4): 645-656, 2003.)

equivalent tools with shorter tool bodies, provided that their mass distribution is similar.

7. All other factors being equivalent, when feed force is large and torque is small, a pistol-grip power tool with a shorter handle should be used. When feed force is small and torque is large, a pistol grip power hand tool with a longer handle is more advantageous.
8. Torque reaction bars help eliminate torque reaction forces, and accessory handles help distribute torque reaction forces among the two hands.
9. A tool counterbalance can help reduce the force needed to support a power hand tool. The optimal location for attaching a balancer is at the tool center of gravity.

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